THIN FILMS RESEARCH

IMPEDANCE CHARACTERISTICS
OF
IRRADIATED THIN FILMS

NGR 44-007-006

THIN FILMS RESEARCH LABORATORY

PROGRESS REPORT NO. 2

December 1, 1967

SOUTHERN METHODIST UNIVERSITY DALLAS, TEXAS

INSTITUTE OF TECHNOLOGY

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Final Report

on

Impedance Characteristics of Irradiated Thin Films

Report No. NGR 44-007-006-2

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ABSTRACT

The complex electrical impedance characteristics of thin (of the order of 1000 A) bismuth films at infrared frequencies corresponding to the region between 2 and 15 microns are discussed. Equivalent electrical circuits are derived for films having initial resistances in the range between 34 and 350 ohms per square, making use of theory from transmission-line analysis and of measurements of film resistance and infrared transmission.

The electron beam irradiation of thin conducting films is considered, and particular problems associated with the determination of irradiation-induced characteristics of thin bismuth films are discussed. The development of instrumentation and techniques for solving these problems is presented.

In addition, because the grant under which the research described above was conducted was aimed in part at the development of an improved research competence at Southern Methodist University, several facets of the unusual strengthening of this competence which has occurred solely because of the NASA multidisciplinary grant for this study of impedance characteristics of thin films are described in an Appendix.

Preface

The work described herein was supported primarily by the National Aeronautics and Space Administration under Grant NGR 44-007-006. Some support was provided also by the Department of Electrical Engineering at Southern Methodist University.

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1. INTRODUCTION

This is the final report on a research project to determine the impedance characteristics of irradiated thin films.

Research planned in the original proposal for this project sought to determine the effect of electron beam irradiation upon some of the characteristics of thin films by

1. Verifying and extending the impedance characteristics previously observed (in a limited number of experiments) in the infrared region for films of bismuth with initial resistance below 300 ohms; and by

2. Determining the effect which electron beam irradiation may have upon the complex impedance characteristics determined in Part 1.

The schedule of activity for conducting this research called for three man-years of effort. The funding for the project continued for one and one-half man-years and then was terminated. Progress of the work at that time was on schedule. In addition, in work vitally important to the success of the project yet not scheduled in nor charged to the budget nor to the University, the Principal Investigator had supervised the design and construction of an $85,000.00 University electron microscopy laboratory in which the irradiation studies could be conducted properly. (This was done after it was determined that scheduling and capability of locally available electron microscopy facilities were going to be inadequate.)

The first part of this report will review the theory of the determination of the complex impedance of a thin film and will present the results of the research carried out on this project, comparing them with previously obtained results of efforts to obtain equivalent circuits and complex impedances for evaporated thin films. It will be shown that there is good agreement with previous work. This will be followed by a discussion of the extension of this work to provide insight into the nature of equivalent circuits for bismuth films having initial resistances down as low as 34 ohms and as high as 370 ohms. The equivalent circuits, including values for the resistances and capacitances involved, for films within this range will be given.

The second part of the report will discuss the general and the special problems to be dealt with in the irradiation of bismuth films. Progress which has been made in handling these problems, including developments in the knowledge, control, and stabilization of a number of film and irradiation variables will be presented.

Finally an appendix is included in order to discuss benefits which have accrued to the University because of this grant for thin films research. It is pointed out that there are three principal benefits: 1) the establishment of the first electron microscopy laboratory at Southern Methodist University; 2) the enhanced capability of the Thin Films Research Laboratory at the University; and 3) the attraction of new faculty and the resulting establishment of new courses, new research, and extended relations with other universities. This information is included here also because the Principal Investigator has been involved in obtaining all three of these benefits, and directly responsible for the first two.

(It is expected that the results of the studies on bismuth films will be included in a paper on the impedance characteristics of thin films to be submitted for publication this year.)

(It is also expected that continued support for this work will be sought both from NASA and from NSF.)

2. IMPEDANCE CHARACTERISTICS OF THIN BISMUTH FILMS

2.1 Introduction

In previous work[1-6] the Principal Investigator and C. E. Drumheller developed and explored theory relating the optical characteristics of a thin film, α, β, and γ (reflection, absorption, and transmission) to electrical properties of the physical structure of the film. Using the results of this work and measurements of the initial electrical resistance and the transmission at infrared frequencies, it was possible to derive an equivalent circuit and a complex impedance value which would adequately predict film behavior. This development was carried out in the rock salt (2 to 15 microns) region of the infrared, but was valid principally for films having low initial values of resistance. The research made use of information and characteristics of films having initial values of resistance ranging over several decades; however, demonstration of validity of the concept was given only for films having initial values of resistance of approximately 90 ohms. The first goal of present research was the establishment of a range of initial resistances for which an equivalent circuit could be established. In particular it was proposed to consider films having initial resistances as low as approximately 10 ohms and as high as 300 ohms. The lower limit was determined by previous difficulties in obtaining good electron micrographs (and therefore good structure appraisal) at this thickness. The upper limit was determined by the fact that between 300 and 400 ohms there appears to be a transition region separating films which are stable over long periods from those which are not. The boundaries are not well-defined (see the section on Special Problems With Bismuth).

The preparation of the films used as specimens in this work has been described in detail in Progress Report 1[7] and will be only superficially reviewed here for reference. This applies also to the measurement techniques. These specimens

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Superscripts refer to numbered items in the LIST OF REFERENCES on page 59.

are 15 x 15 mm squares of bismuth film formed by vacuum deposition through a mask onto a 350-angstrom-unit-thick substrate of cellulose nitrate. The substrate is mounted on a square open frame having one pair of opposite sides made of Lucite and the other sides made of brass. (See Fig. 1) The bismuth was deposited at a pressure of 3 x 10^{-7} mm Hg.

Film resistances were measured with very low-level inputs using an off-balance bridge. Resistance of one film of a set (of four) was monitored during each evaporation.

Infrared transmission measurements in the 2- to 15-micron region were made on a Beckman IR-5 spectrophotometer.

Essentially every aspect of the preparation, control, and measurement of the films used in the current research was similar to that of previous work. There was one exception: these films were prepared at an approximate order of magnitude better vacuum than earlier films. In general, the resistance measurements, infrared data, electron micrographs, and complex impedance analyses verify the validity and usefulness of previous work.

2.2 The Determination of Film Impedance

The concept of complex electrical impedance for a thin film was developed as a useful way to provide a physical interpretation for observed thin film optical properties. It was found that the value of resistance can be determined from the dc resistance and a statistical consideration of grain boundary resistance distribution. The value of reactance can be determined from infrared transmission measurements and the result of a transmission line analysis. Results from past work have indicated that the reactance is capacitive and may be attributed to a dielectric of oxide between grain boundaries. The transmission line analysis will now be developed briefly, and the results necessary for equivalent circuit

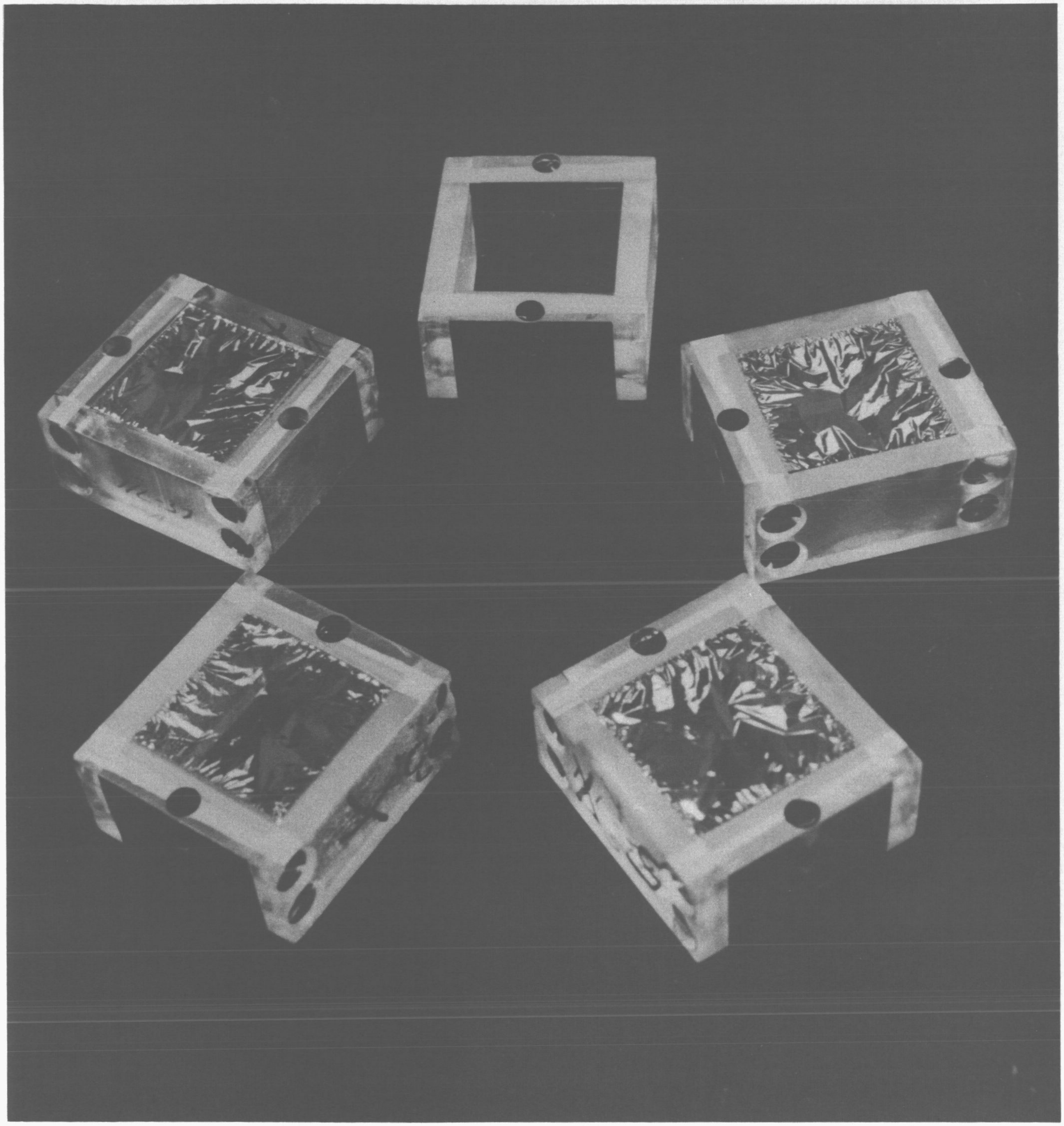
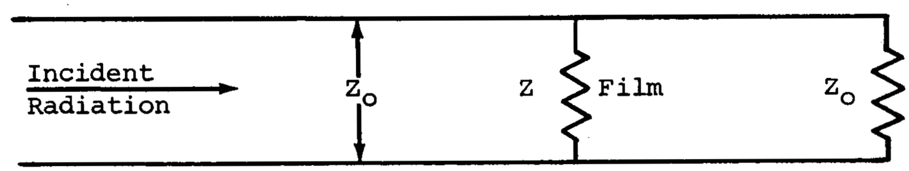


Fig. 1. Typical Set of Four Evaporated Bismuth Films Shown on Their Supporting Substrate Holders. The fifth holder (at the top of the picture) supports only a cellulose nitrate substrate which is always used with this set as a reference during infrared measurements. There is no bismuth on it. Films sometimes develop wrinkles upon aging. (Magnification: approximately 2X)

determination will be obtained. Thereafter, calculations will be made to determine equivalent circuits for nine typical films from the fifteen sets of four films on which data were taken.

A transmission line analysis is possible if the following circuit is assumed



where, if[8]

$$K = \frac{Z_O - Z_T}{Z_O + Z_T} \qquad (1)$$

$$W = \frac{E^2(Z + Z^*)}{2ZZ^*} \qquad (2)$$

α, β, and γ can be determined as follows:

$$\alpha = \frac{Z_O{}^2}{Z_O{}^2 + 2Z_O(Z + Z^*) + 4ZZ^*} \qquad (3)$$

$$\beta = \frac{2Z_O(Z + Z^*)}{Z_O{}^2 + 2Z_O(Z + Z^*) + 4ZZ^*} \qquad (4)$$

$$\gamma = \frac{4ZZ^*}{Z_O{}^2 + 2Z_O(Z + Z^*) + 4ZZ^*} \qquad (5)$$

Where Z_O = 376.6 ohms per square

K is the reflection coefficient

Z_T is the impedance seen by the incident radiation

Z is the impedance of the film

W is the power delivered to the film

E is the voltage across the film

α is the fraction of incident power reflected by the film

β is the fraction of incident power absorbed by the film

γ is the fraction of incident power transmitted by the film

Now if a simple series circuit is assumed as an accurate representation of Z, and $Z = R + jX$, equation (5) yields

$$\left(\frac{X}{R}\right)_s^2 = \frac{\gamma\left(\frac{Z_o + 2R}{2R}\right)^2 - 1}{1 - \gamma} \tag{6}$$

If, on the other hand, a simple parallel circuit is assumed, equation (5) yields

$$\left(\frac{X}{R}\right)_p^2 = \frac{\gamma\left(\frac{Z_o}{R}\right)^2}{4 - \gamma\left(\frac{Z_o + 2R}{R}\right)^2} \tag{7}$$

Equation (5) is chosen because γ is relatively easy to measure, and thus these expressions can be examined experimentally.

If the foregoing relations (Equations 6 and 7) between γ and R (where R is a measured film resistance in ohms per square) are plotted[9] (Fig. 2) for constant ratios of $\left(\frac{X}{R}\right)$, both for the series and for the parallel cases, and then if experimental values of γ and R are plotted on the same graph, it is found that the experimental curve does not completely fit the case for $\left(\frac{X}{R}\right) = 0$ (the case in which the film is purely resistive)*. From these and other data, one can infer[10,11] however, that the films behave like the graphical predictions for the parallel circuit case at values of DC resistance (R) above approximately 1,150 ohms. Also, the films behave like predictions for the series circuit case at values of DC resistance below approximately 1,150 ohms. This behavior is readily related[10] to structure.

It is possible also to deduce[10,11] from the data a strong indication that the series circuit is composed of resistance and capacitance in series, and, in addition, that it is not resistance and inductance in series. Similarly, it is

*Skin effect calculations indicate that there should be no change in resistivity from DC through the infrared for films having thicknesses of the order of those being considered (~1000 A).

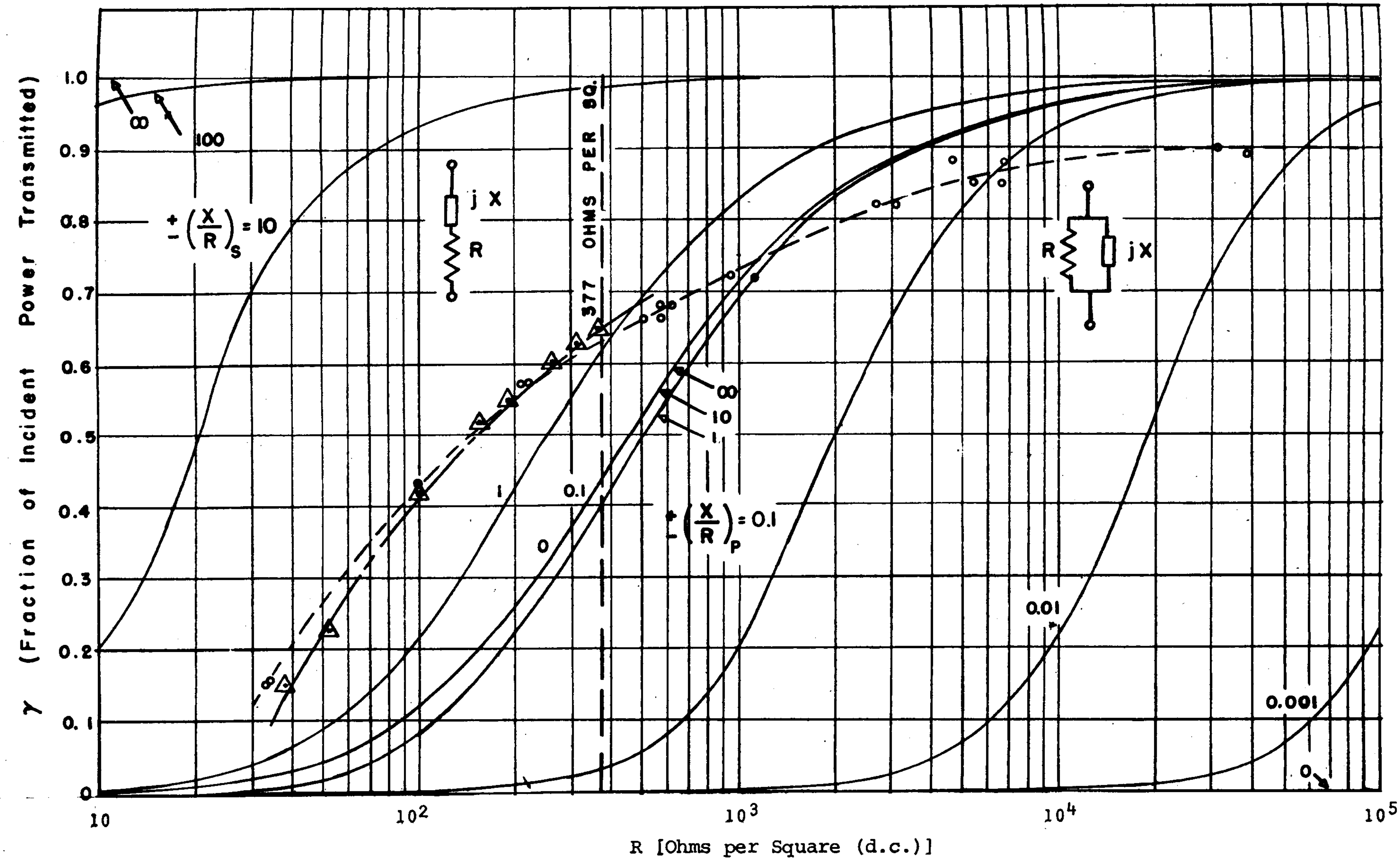


Fig. 2. Transmission Coefficients of Evaporated Bismuth Films for Radiation at $\lambda = 14\mu$
(o Film deposited at 5.3×10^{-5}mm Hg; Δ Film deposited at 7.3×10^{-7}mm Hg.)

possible to infer that the parallel circuit is resistance and capacitance in parallel, and that is not resistance and inductance in parallel. Further, it has been shown[11] that either one of these types of circuits alone is not an adequate representation of the film characteristics.

The simple series-parallel circuit in Fig. 3 was suggested[11] as a more reasonable possibility,

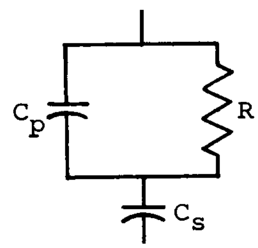


Fig. 3 Series-Parallel Circuit, $C_p = C_s$

and its validity was established by: (1) drawing inferences regarding physical structure from electron micrographs; (2) making assumptions as to the source of the resistance and capacitances; and (3) postulating that, since the film has a measurable DC resistance, this circuit is valid for areas of the film in which the dimensions are small compared to the wavelength (of the incident radiation).

Continuing the transmission line analysis it is now possible, assuming that the equivalent circuit for the film is that of Fig. 3, to determine values for C_s, C_p, and R. First, one assumes $C_s = C_p$ (=C). Previous experience[11] indicates that the value of $R = \frac{1}{2}R_{DC}$. These relations are then used in the general expression for the impedance of the series-parallel equivalent circuit which follows.

$$Z = \frac{RX^2}{R^2 + X^2} + j\left[X + \frac{R^2 X}{R^2 + X^2}\right] \tag{8}$$

Now if this expression for Z is substituted into the general expression for transmission, Eq. (5), one obtains

$$\gamma = \frac{4R^2 + X^2}{\left(\frac{Z_o}{2}\right)^2 \frac{R^2 + X^2}{X^2} + Z_oR + (4R^2 + X^2)} \tag{9}$$

The problem of finding X (and from it, C) is extremely involved, and it is helpful to make use of quadratic notation. Solving Eq. (9) for X^2 yields

$$X^2 = \frac{-b + \sqrt{b^2 - 4c}}{2} \tag{10}$$

where $$b = 4R^2 - \left(\frac{\gamma}{1-\gamma}\right)\left[Z_oR + \left(\frac{Z_o}{2}\right)^2\right] \tag{11}$$

$$c = -\left(\frac{\gamma}{1-\gamma}\right)\left(\frac{Z_o}{2}\right)^2 R^2 \tag{12}$$

substituting $X = \frac{\lambda}{2\pi \underline{c} C}$ in Eq. (10) one obtains the desired equation

$$\frac{1}{2\pi \underline{c}}\left[\frac{2}{-b + \sqrt{b^2 - 4c}}\right]^{\frac{1}{2}} = C\,\frac{1}{\lambda} \qquad (\underline{c} \text{ is the velocity of light}) \tag{13}$$

When the circuit of Fig. 3 is a valid equivalent for a film, Eq. (13) must hold; and a plot of the left-hand side against the frequency ($1/\lambda$) should be linear and should pass through the origin with a slope equal to the capacitance, C. Plots of Eq. (13) have been obtained for film specimens having a wide range of initial resistances, and will be displayed and discussed later. The information which can be inferred from them is one of the major results of this paper. It is useful first, however, to compare the results of the present research on 100-ohm films with previous work on a 90-ohm film, because of the proximity of the two initial resistance values.

An equation similar to Eq. (13) is valid for the simpler case in which the equivalent circuit is a capacitance in series with a resistance (instead of with a resistance and capacitance in parallel).

It is

$$\frac{1}{2\pi CR}\left[\frac{1-\gamma}{\gamma\left(\frac{Z_o + 2R}{2R}\right)^2 -1}\right]^{\frac{1}{2}} = c\left(\frac{1}{\lambda}\right) \tag{14}$$

In previous research the curve of Fig. 4 was a plot of Eq. (14) and, for a film having an initial resistance of 90 ohms, yielded a value of 3.8×10^{-5} μμf/square for capacitance. In recent research the curve of Fig. 5 is a plot of Eq. (14) obtained from a film having an initial resistance of 100 ohms. From this curve it is possible to infer a capacitance of 3.55 x 10 μμf. This is excellent agreement. A bismuth film whose initial resistance is 100 ohms is thinner than a bismuth film whose initial resistance is 90 ohms. The inter-grain capacitance, therefore, could be expected to be smaller.

In Figs. 4 and 5 a dotted vertical line can be seen near the 1/λ value of 2000 cm^{-1}, and should be explained. One side is labelled "series" and the other, "parallel", to delineate the transition value of frequency, on the one side of which the film behaves like a series circuit, and on the other side of which the film behaves like a parallel circuit. This may be understood by an examination of Fig. 2. Here the transition value varies and it is seen to be dependent upon resistance. The effective value for any given film is found by determining the frequency at which plots of theoretical and experimental transmission values intersect. Figure 6 is a plot of previous experience with 90-ohm films. The transition frequency is approximately 1780 cm^{-1}. A similar plot (Fig. 7) of recent experience which includes 100-ohm films is almost identical, and yields a transition frequency of 1700 cm^{-1}. Now since the calculations for which data are plotted in Figs. 4

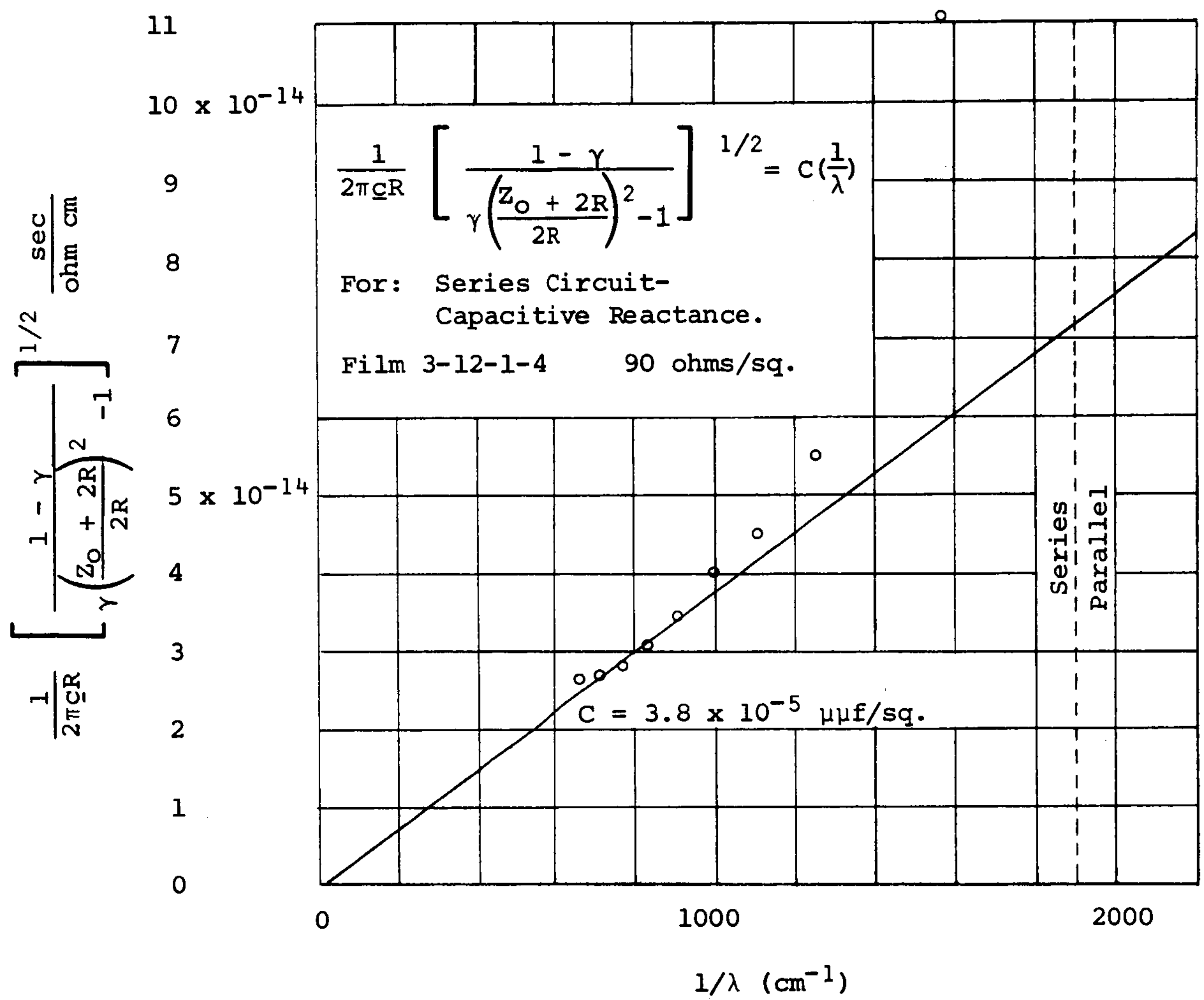


Fig. 4. Determination of The Capacitance Value Assuming A Resistance-Capacitance Series Circuit As A Possible Film Impedance (90-Ohm Film).

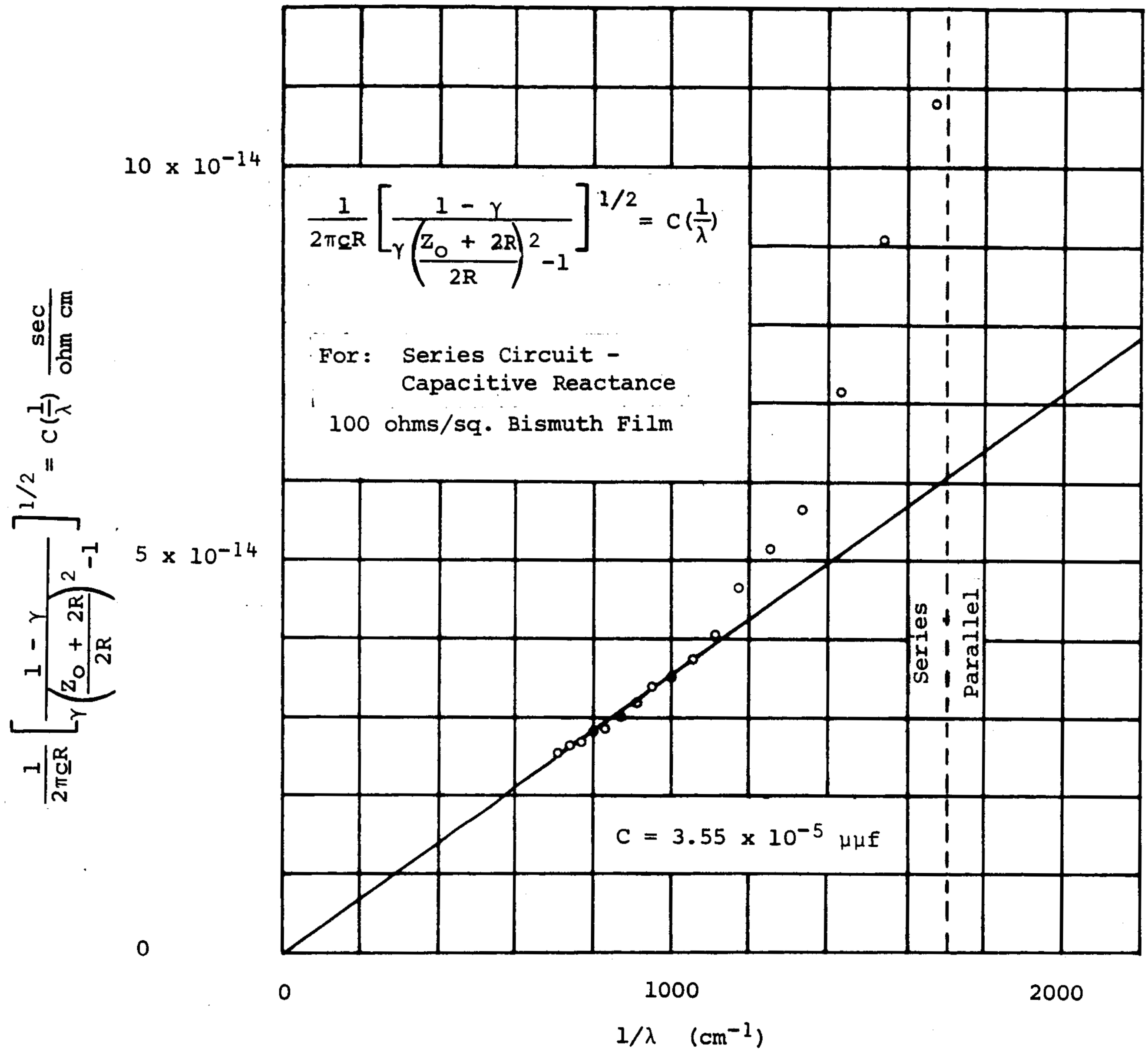


Fig. 5. Determination of The Capacitance Value Assuming A Resistance-Capacitance Series Circuit As A Possible Film Impedance (100-Ohm Film).

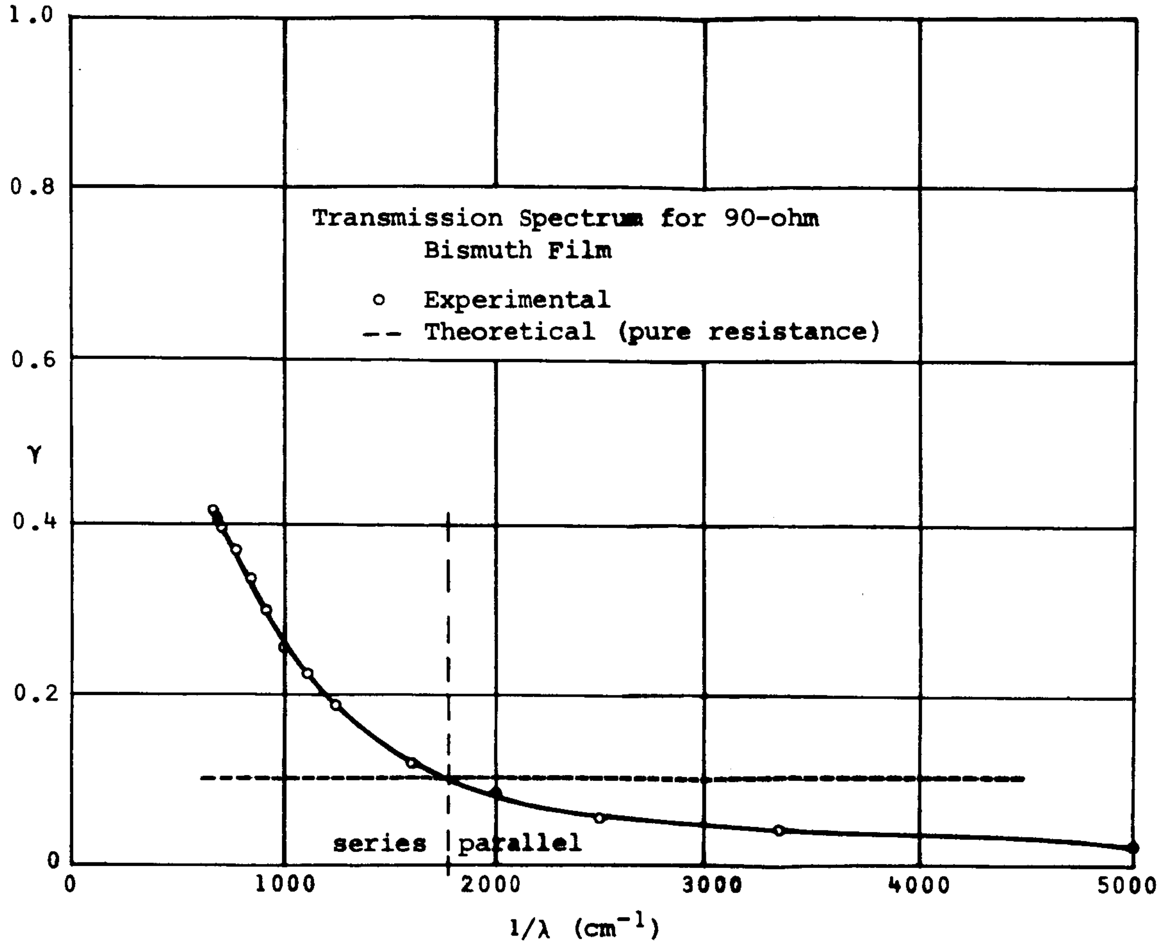


Fig. 6. Frequency Variation of Infrared Transmission for 90-Ohm Films.

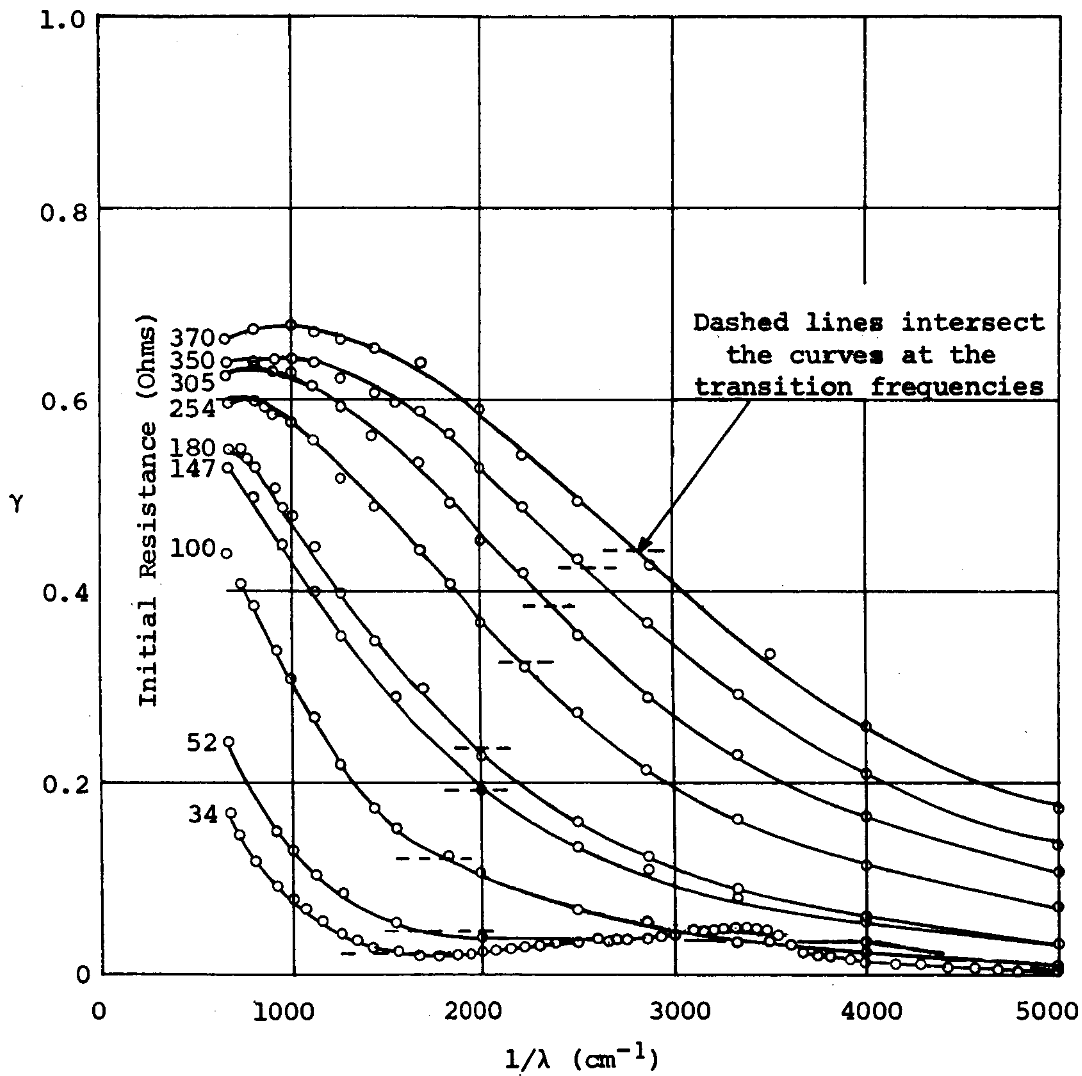


Fig. 7. Transmission Spectra for Evaporated Bismuth Films Immediately after Deposition.

and 5 were obtained assuming a series circuit, it would be expected that the data would deviate increasingly from a straight line as the plot approached the transition frequencies. Those deviating data therefore are not included in the determination of the straight-line relation yielding the capacitance value.

Continuing the comparison with previous work: an equation similar to Eq. (13) was developed for the case in which the equivalent circuit is a capacitance in parallel with a resistance. This equation is

$$\frac{1}{2\pi \underline{c} Z_o} \left[\frac{4-\gamma \left(\frac{Z_o + 2R}{R} \right)^2}{\gamma} \right]^{\frac{1}{2}} = C \ (1/\lambda) \tag{15}$$

The curve of Fig. 8 is a plot of Eq. (15) for a 90-ohm film, and from it a value of capacitance of 3.5 x 10^{-5} μμf per square was determined previously, allowing for uncertainties in infrared measurements and for incomplete data. Recent research has yielded data for the curve of Fig. 9, from which a value for capacitance of 3.9 x 10^{-5} μμf per square has been determined as before for a 100-ohm film. Again this is good agreement.

It is now desirable to check the validity of the values of capacitance determined by the methods just discussed. This is possible by assuming that one actually has the types of circuits for which the capacitances were determined and then by calculating the theoretical infrared transmission which can be expected for these circuits if they contain capacitances of the values determined. These transmission data can then be plotted as a function of 1/λ, and compared with the experimentally determined curve plotted on the same axes. Theoretical infrared transmission values for both series- and parallel-type circuits are plotted together with experimental data from project research in Fig. 10. The validity of the circuits and capacitance values is demonstrated.

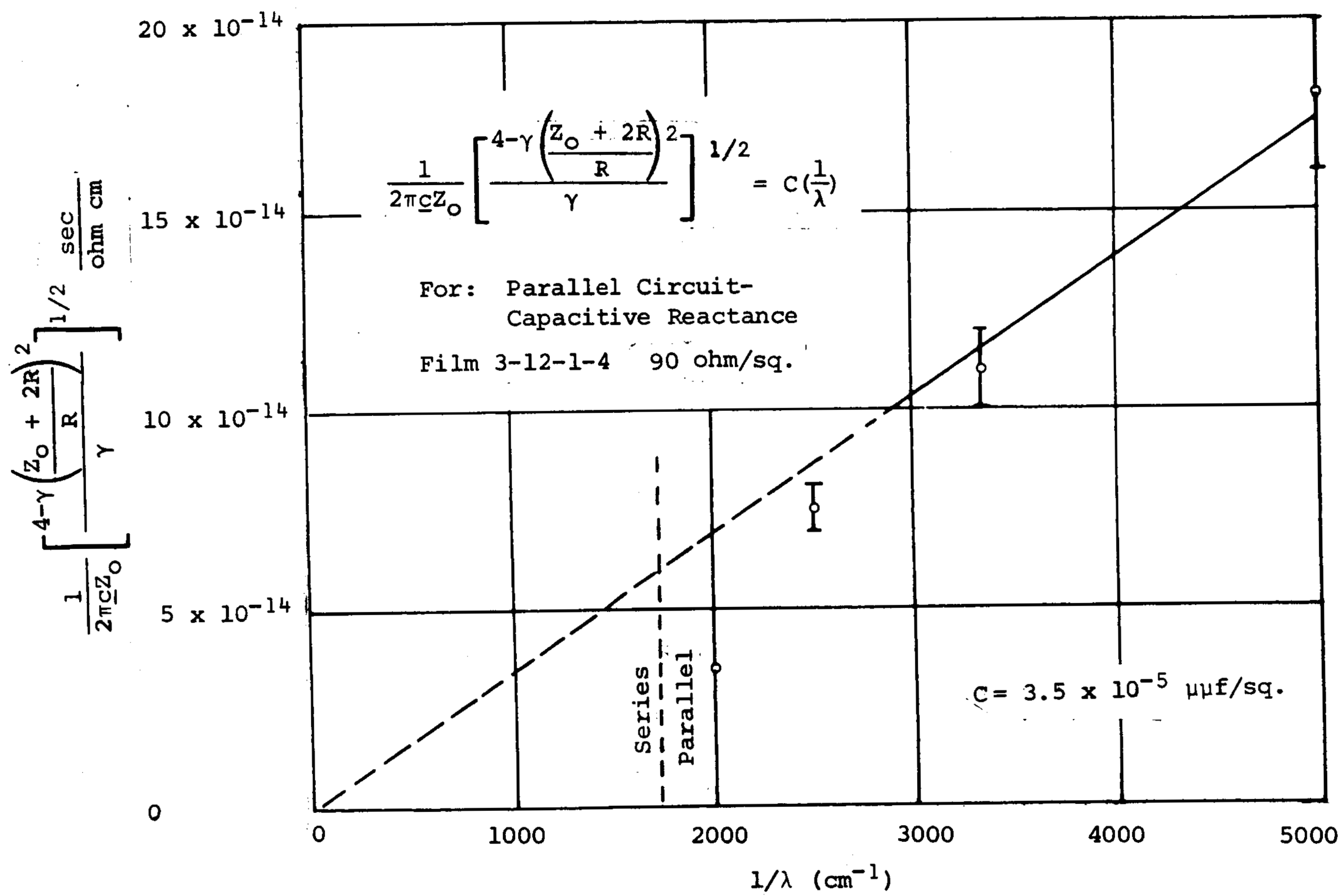


Fig. 8. Determination of The Capacitance Value, Assuming A Resistance-Capacitance Parallel Circuit As A Possible Film Impedance (90-Ohm Films).

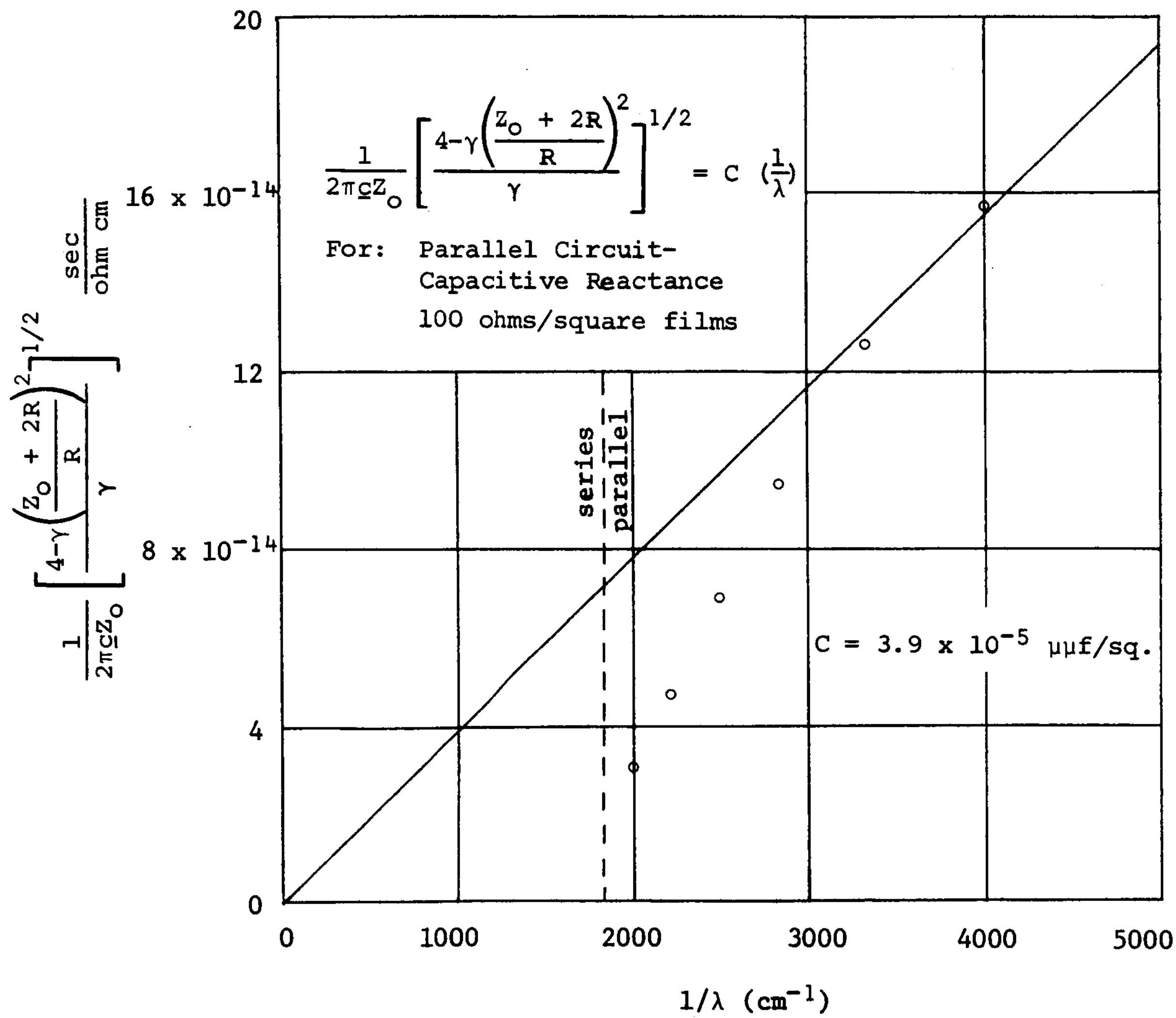


Fig. 9. Determination of The Capacitance Value, Assuming A Resistance-Capacitance Parallel Circuit As A Possible Film Impedance (100-ohm films).

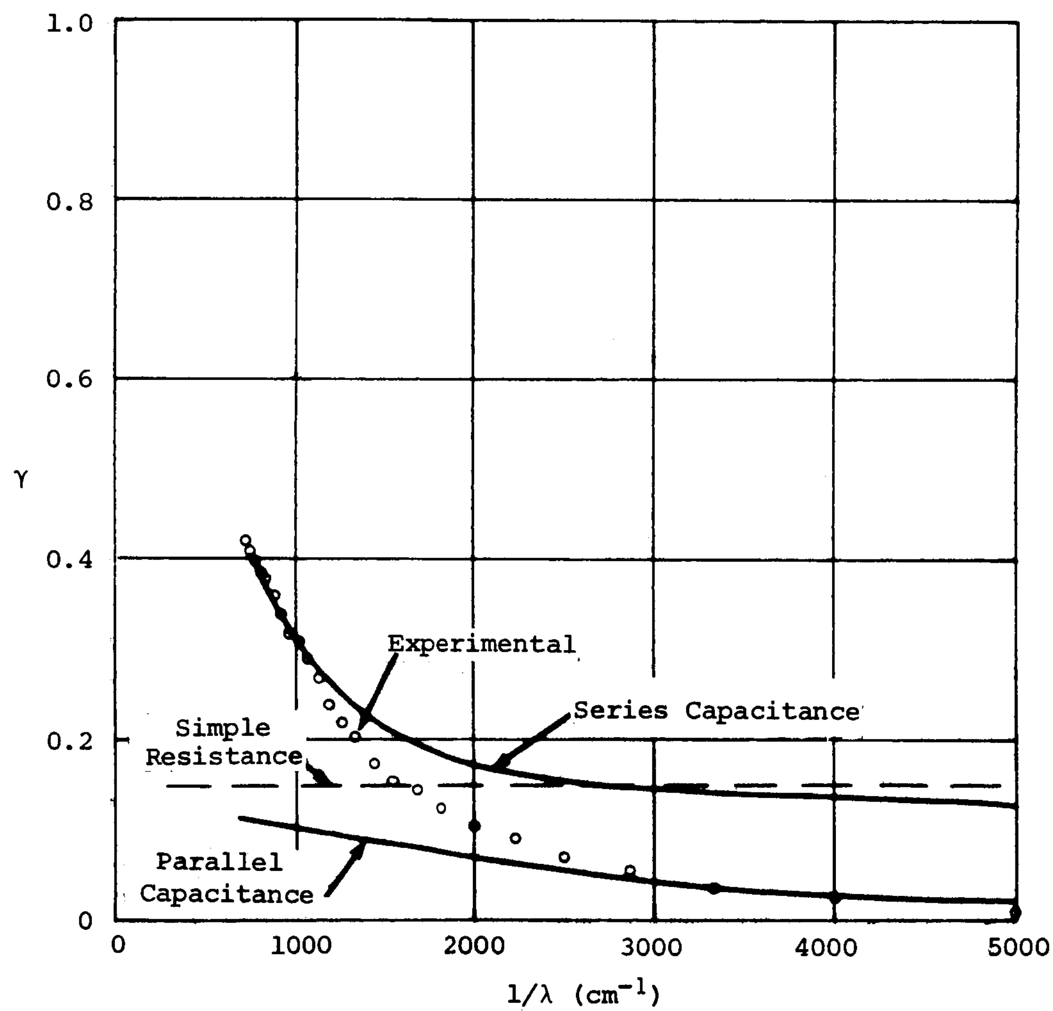


Fig. 10. Transmission Spectrum for Low-Resistance Evaporated Bismuth Films

As would be expected for a simple resistance-capacitance series circuit, the theoretical behavior at high frequencies approaches that of the resistance alone. Correspondingly, the theoretical behavior of a simple resistance-capacitance parallel circuit should approach that of the resistance alone at low frequencies. The results obtained in Fig. 10 are similar to those obtained in previous work[11].

From Fig. 10 it is quite apparent, however, that neither simple circuit is completely representative of the film impedance. Two outstanding facts are evident: 1) the imdepance characteristics are like those of a resistance shunted by a parallel capacitance at high frequencies, and of the same resistance with a series capacitance at low frequencies; and 2) the capacitances in these two cases have essentially the same values. These facts suggest that the film impedance may actually be that of a combination series-parallel circuit. It was for such a circuit that the equation for impedance, Z, given in Eq. (8) was derived and, as previously discussed herein, the equation for determining the capacitance in such a circuit, Eq. (13), was obtained.

Equation (13) was used in previous work with 90-ohm films to obtain a value for C from the plot of data in Fig. 11. A test of the validity of the circuit for which this value of C was obtained is given in Fig. 12. Agreement of the experimental curve with the curve calculated for the series-parallel circuit case is good. It is unusually good when compared with the infrared transmission curve (simple resistance 45 ohms in Fig. 12) which assumes that the film is a pure resistance and has no reactive component. It is also better than the agreement with either of the curves suggested by other types of circuits.

In the research of this project, values for C were determined from a series of curves which are shown in Figs. 13, 14, and 15. The validity of the series-parallel circuits for which these values were obtained can be examined in the calculated and experimental curves of Figs. 16 through 24. First, however, in

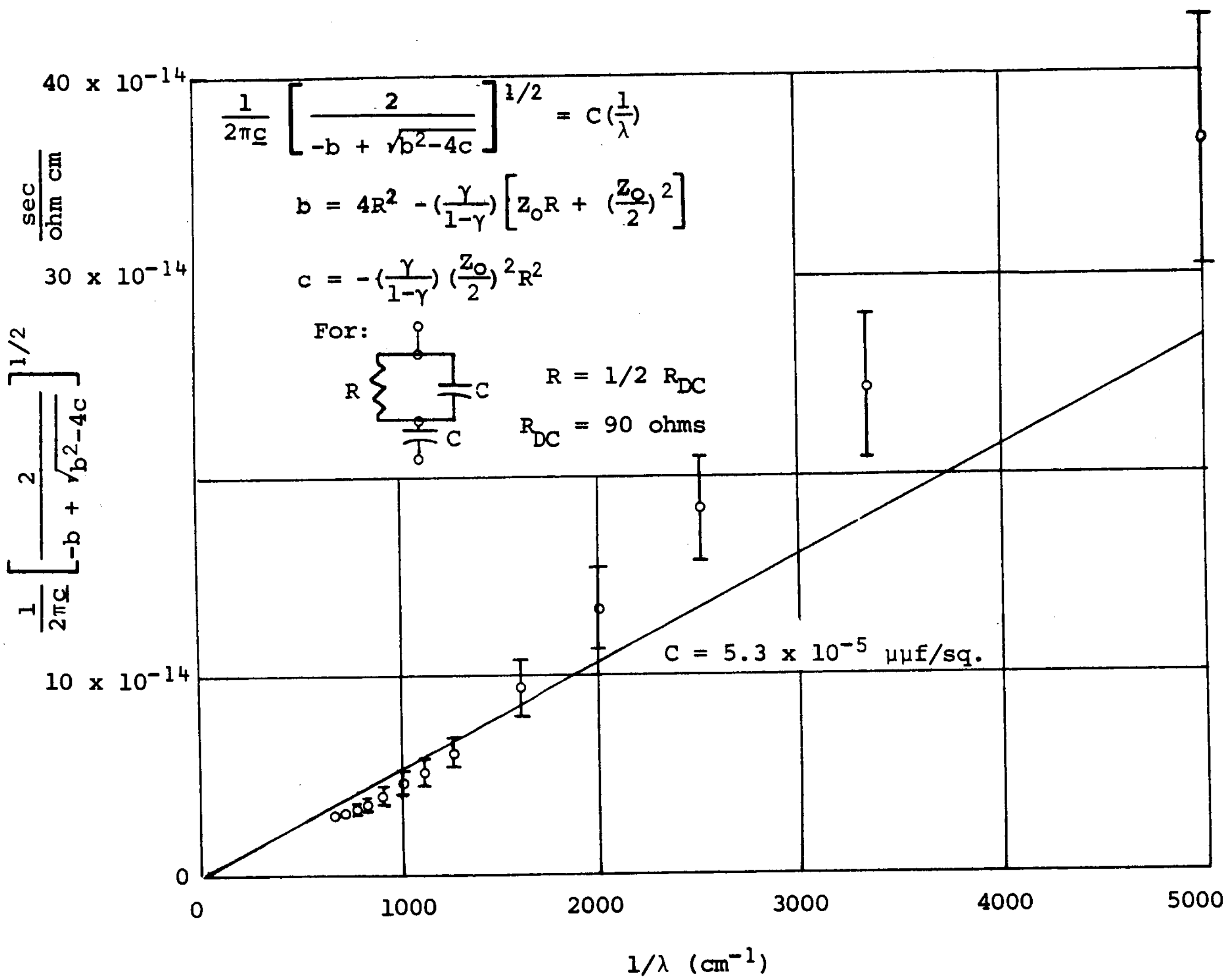


Fig. 11. Determination of The Capacitance Values, Assuming A Combination Series-Parallel Capacitance Circuit As A Possible Film Impedance (90-Ohm Films).

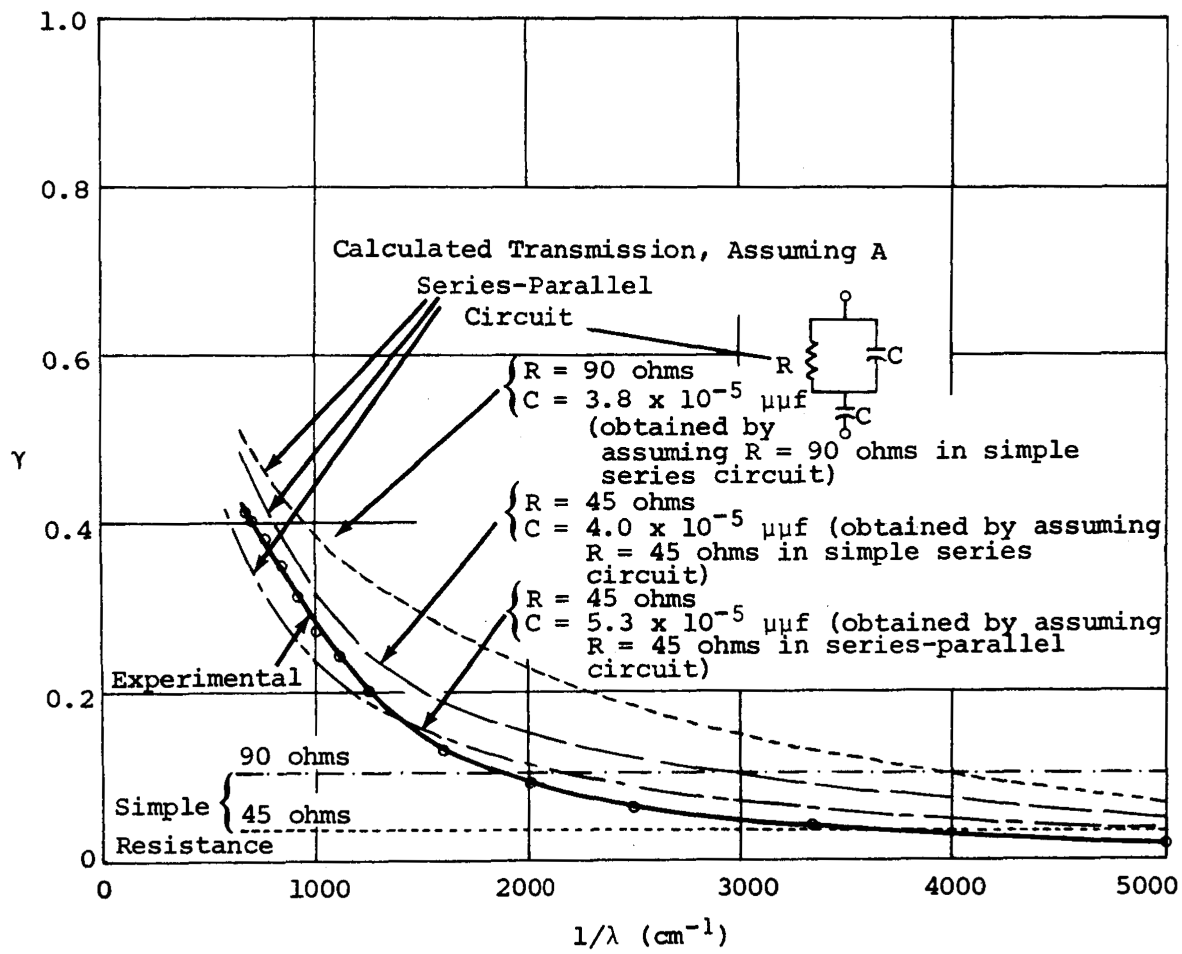


Fig. 12. Calculated and Experimental Transmission Spectra for 90-Ohm Evaporated Bismuth Film.

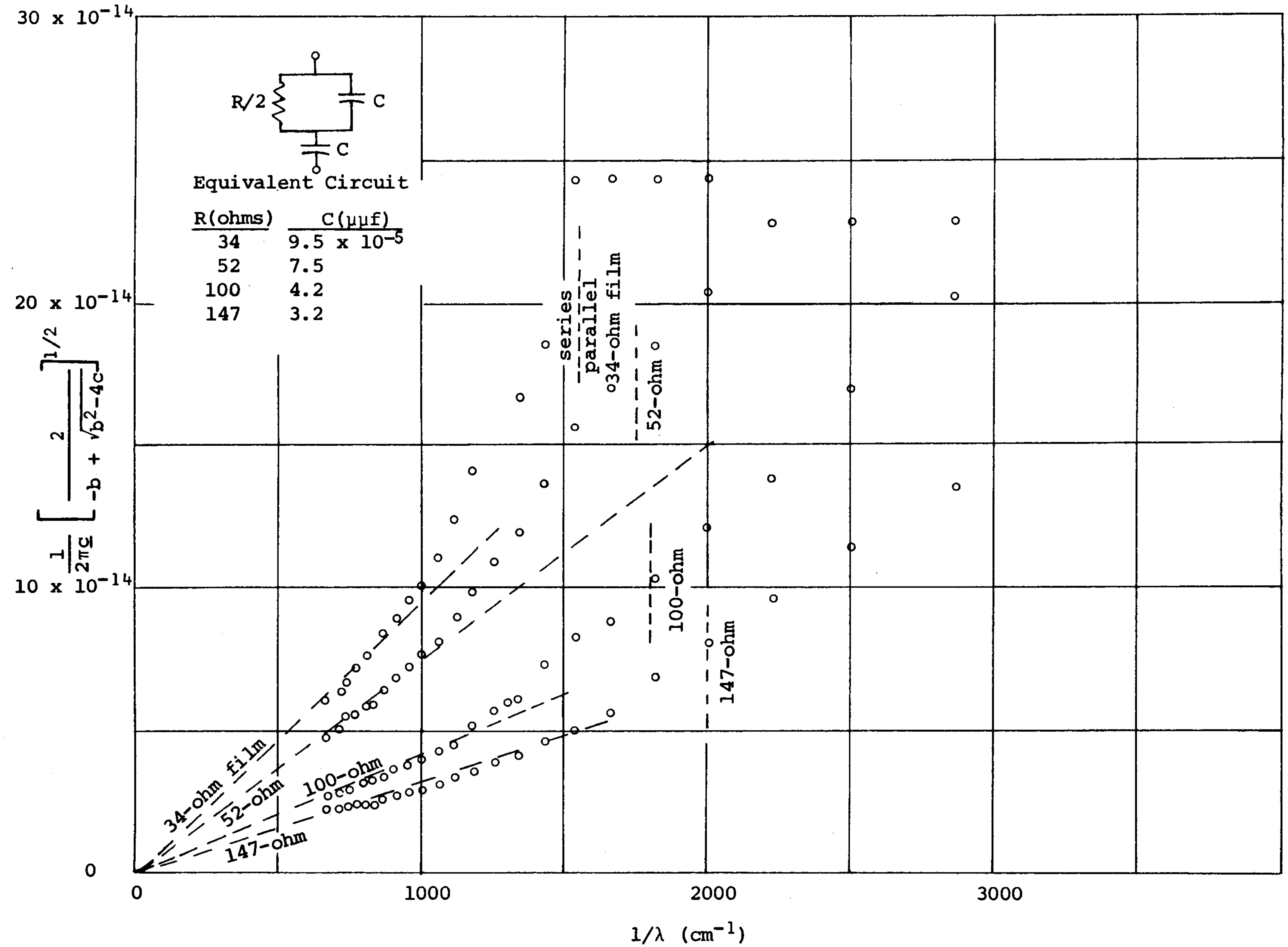


Fig. 13. Determination of The Capacitance Values, Assuming A Series-Parallel Capacitance Circuit (34-, 52-, 100-, and 147-Ohm Films). Transition frequencies are identified by vertical lines corresponding to each value of initial resistance.

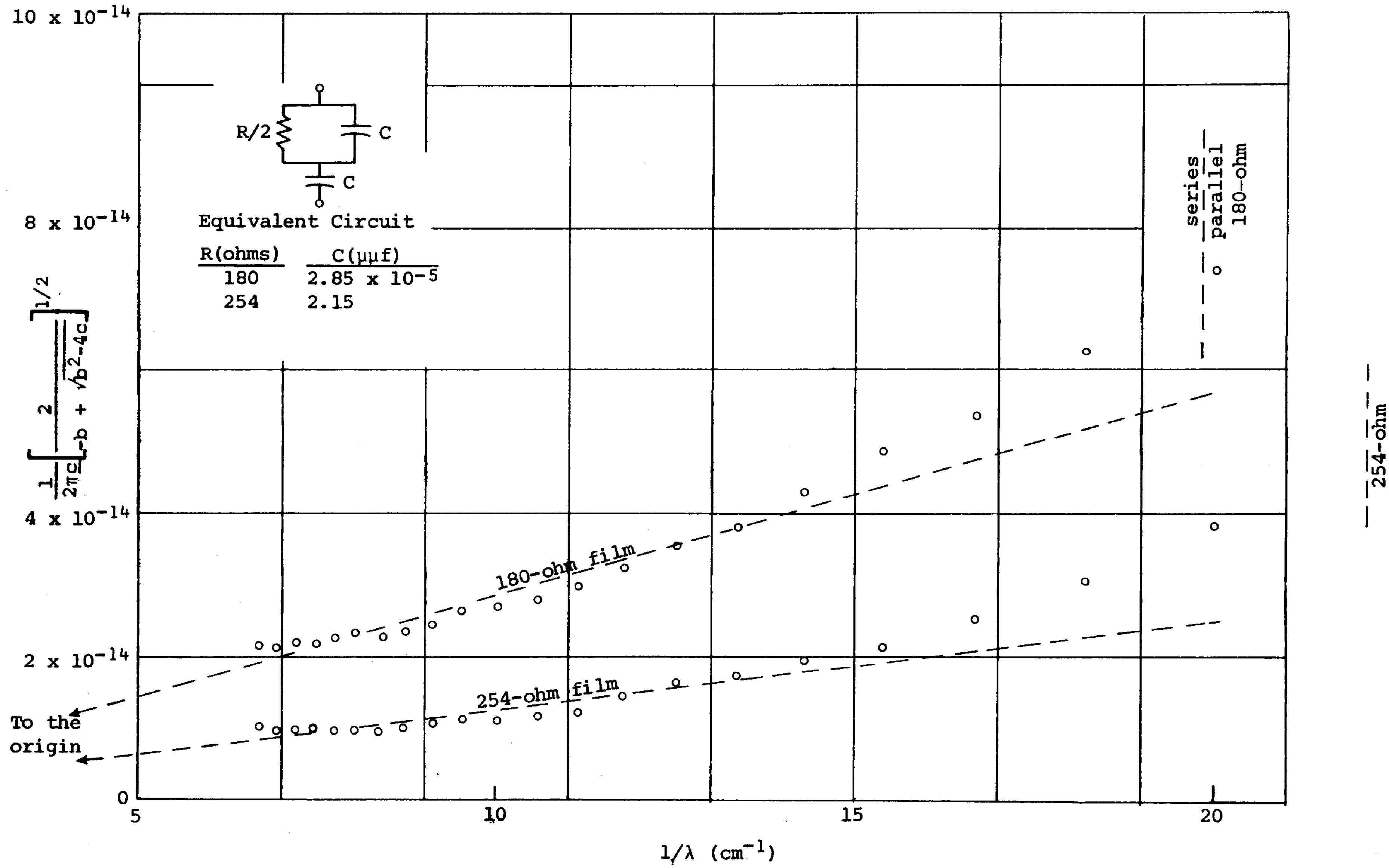


Fig. 14. Determination of The Capacitance Values, Assuming A Series-Parallel Capacitance Circuit (180-, and 254-Ohm Films). Transition frequencies are identified by vertical lines corresponding to each value of initial resistance.

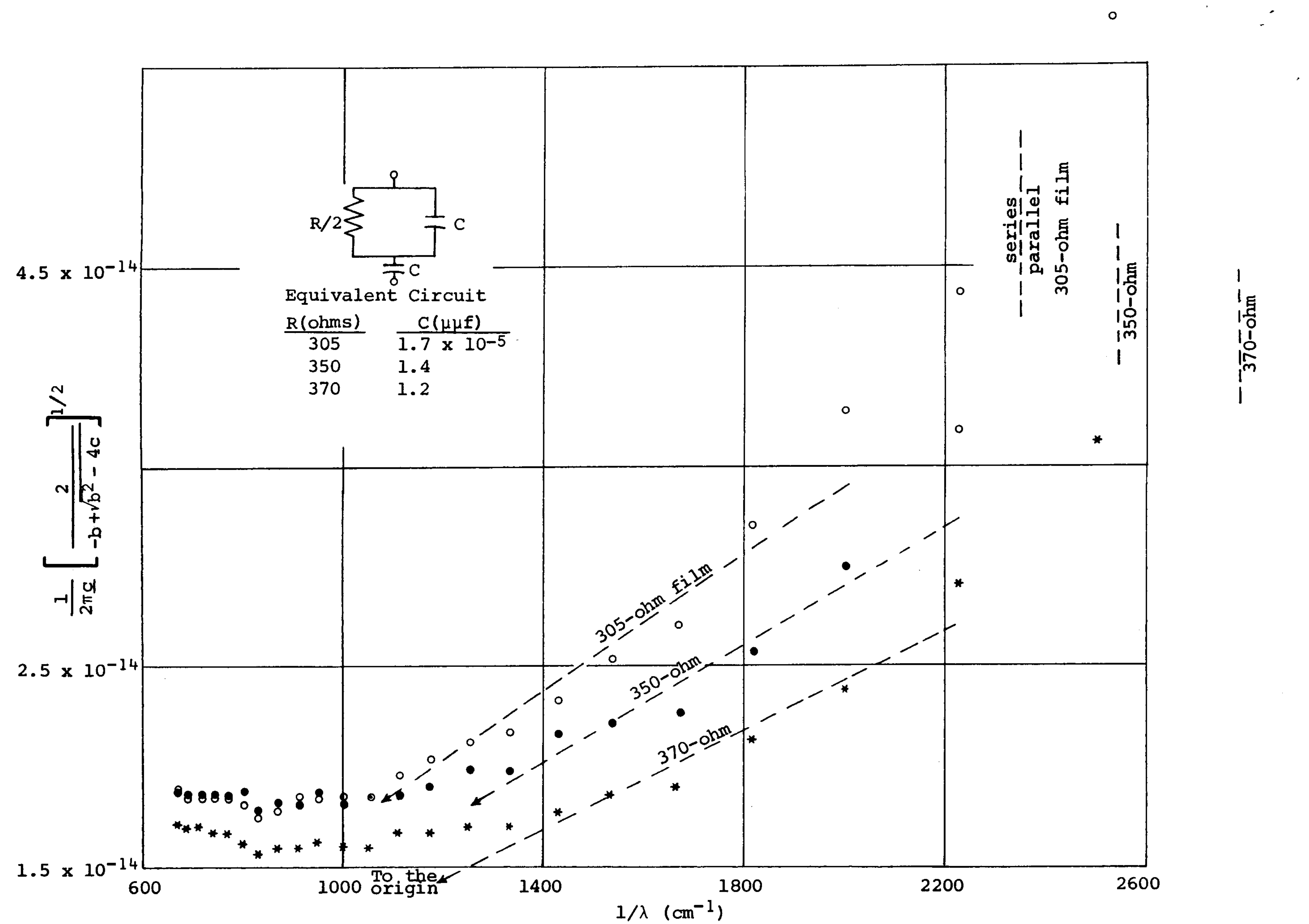


Fig. 15. Determination of The Capacitance Values, Assuming A Series-Parallel Capacitance Circuit (305-, 350-, and 370-Ohm Films). Transition frequencies are identified by vertical lines corresponding to each value of initial resistance.

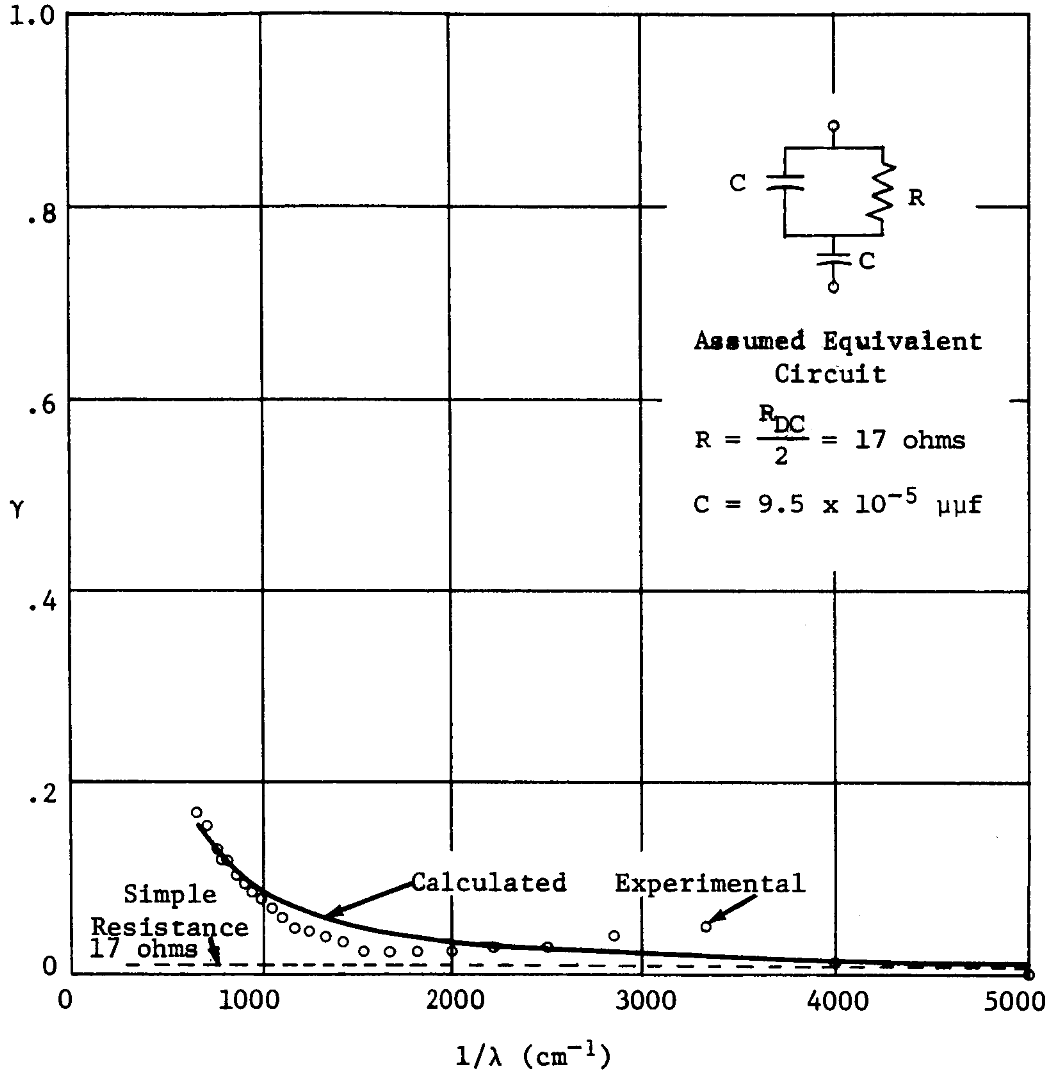


Fig. 16. Calculated and Experimental Transmission Spectra for 34-Ohm Evaporated Bismuth Films.

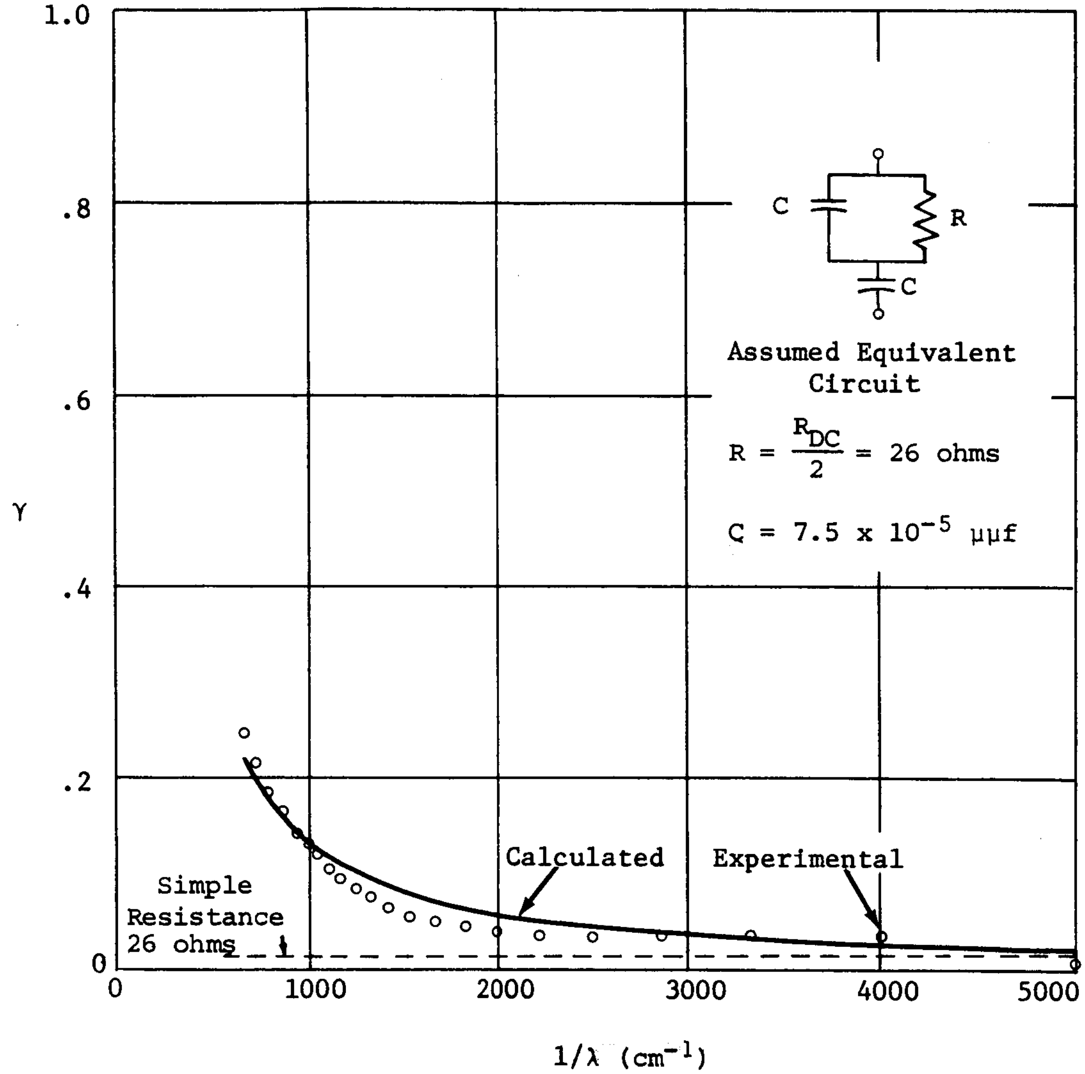


Fig. 17. Calculated and Experimental Transmission Spectra for 52-Ohm Evaporated Bismuth Films.

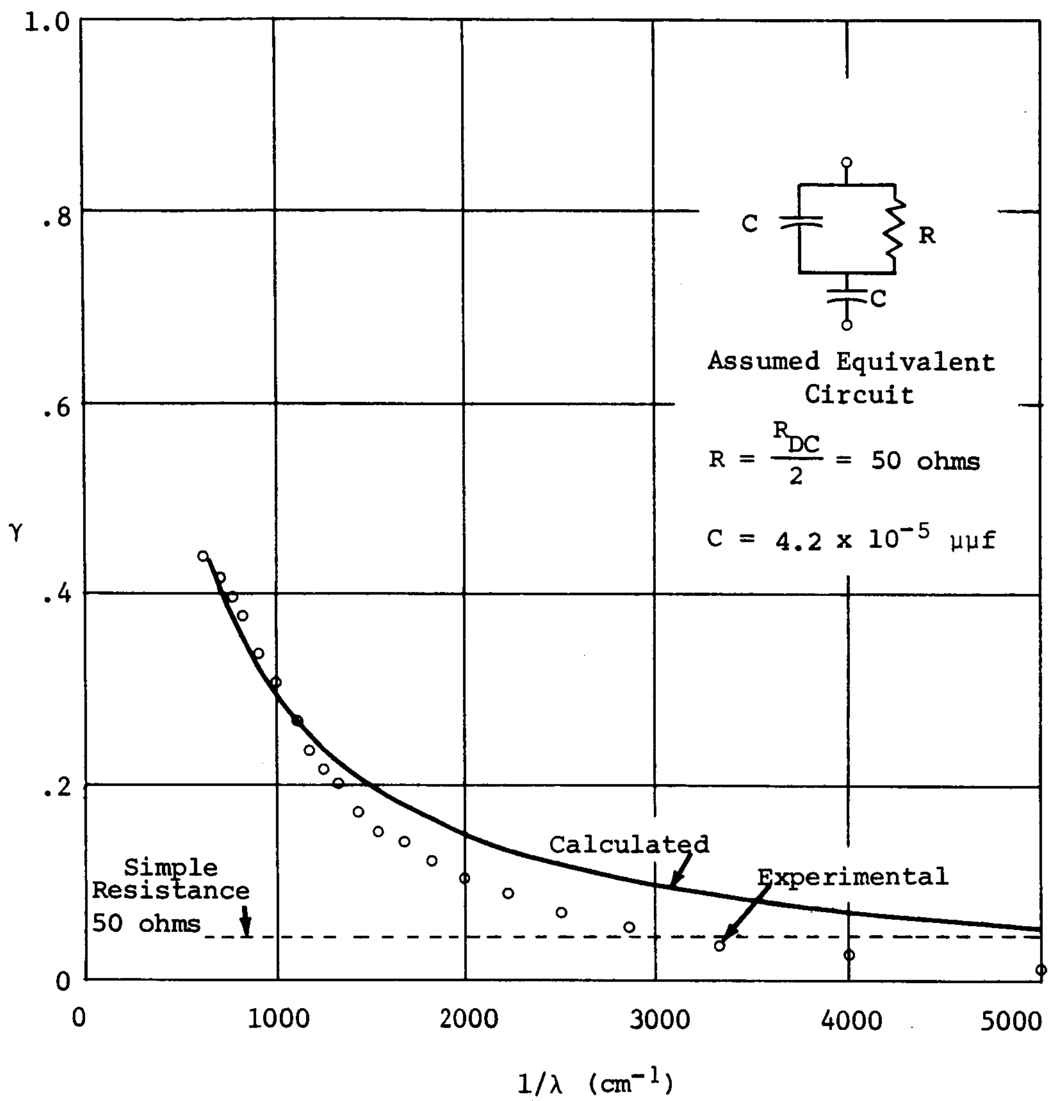


Fig. 18. Calculated and Experimental Transmission Spectra for 100-Ohm Evaporated Bismuth Films.

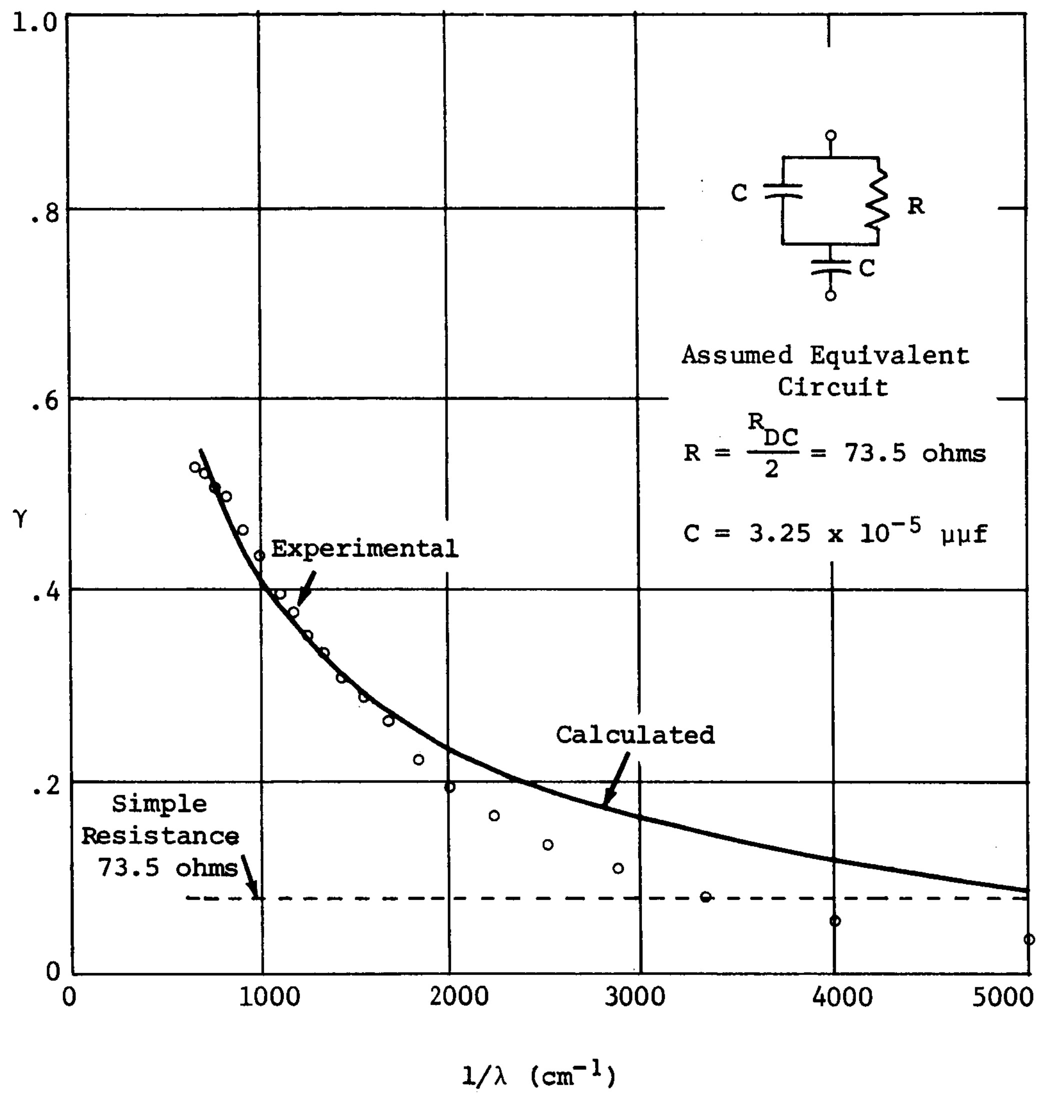


Fig. 19. Calculated and Experimental Transmission Spectra for 147-Ohm Evaporated Bismuth Films.

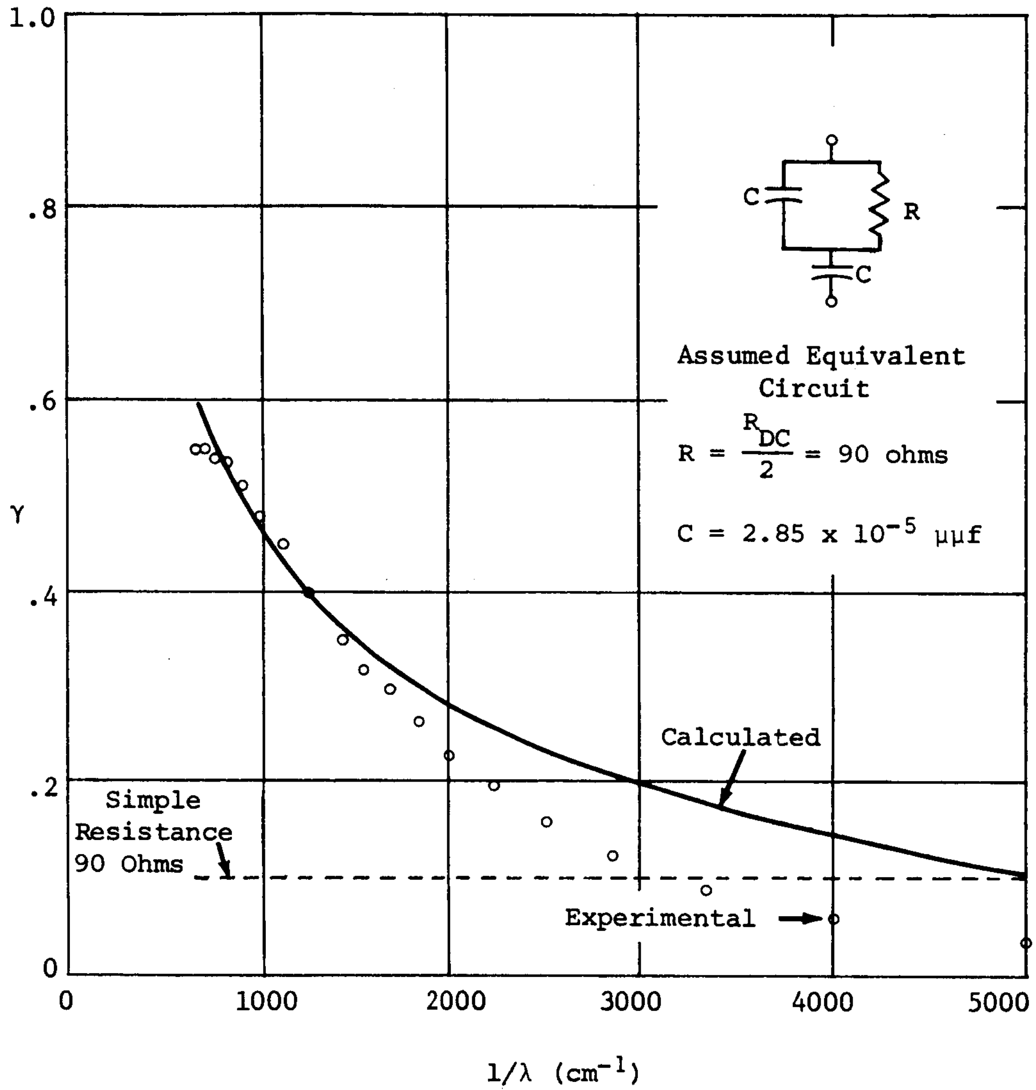


Fig. 20. Calculated and Experimental Transmission Spectra for 180-Ohm Evaporated Bismuth Films

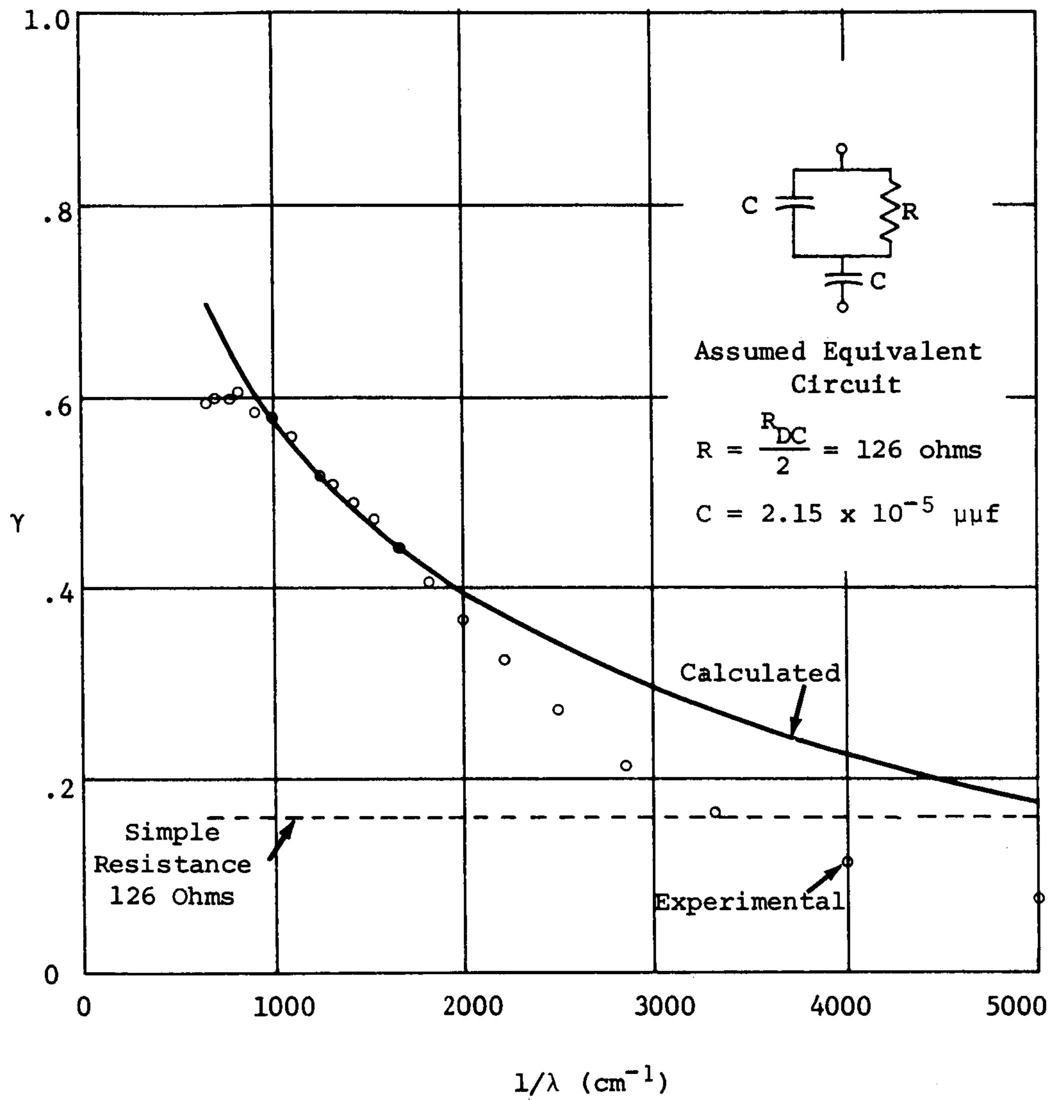


Fig. 21. Calculated and Experimental Transmission Spectra for 254-Ohm Evaporated Bismuth Films.

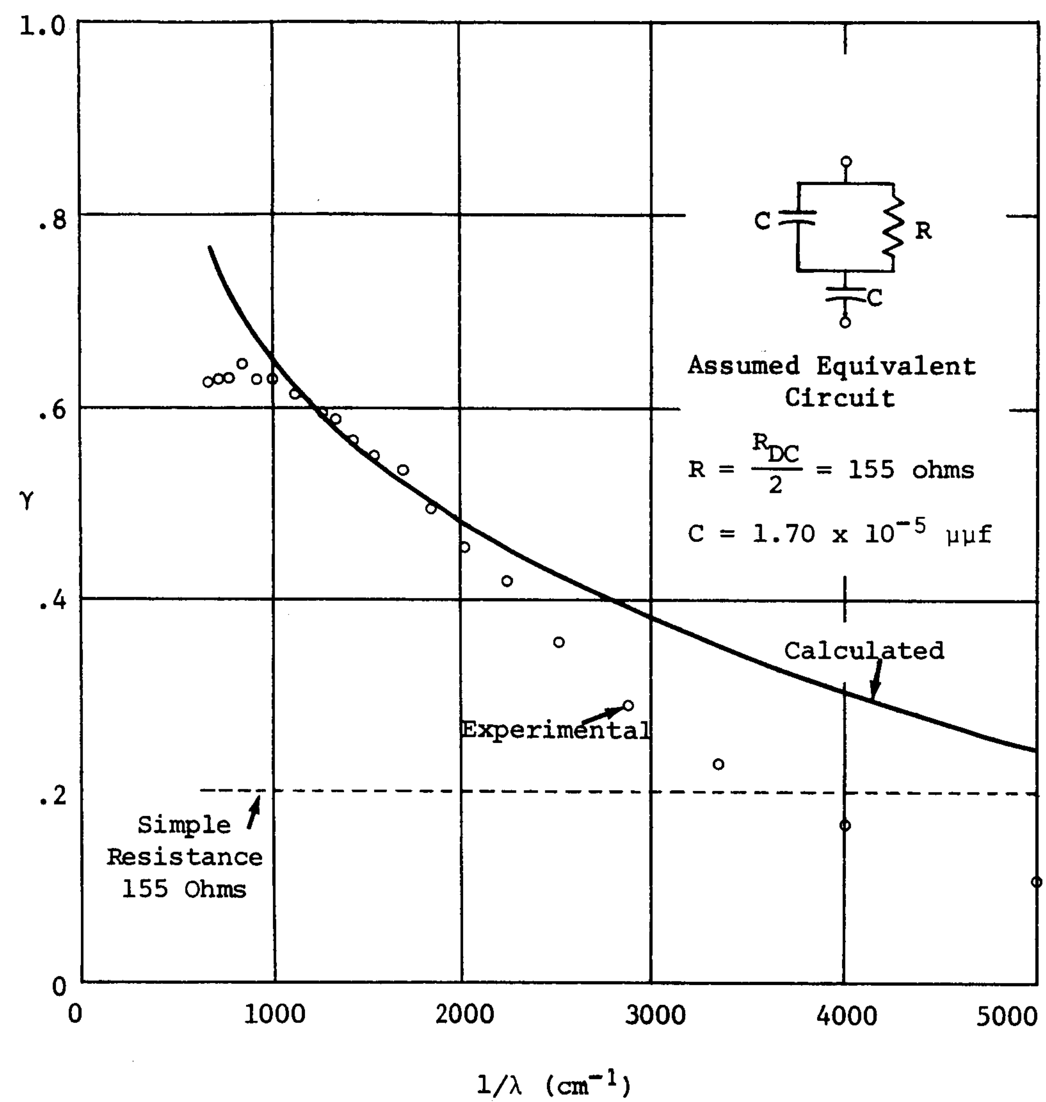


Fig. 22. Calculated and Experimental Transmission Spectra for 305-Ohm Evaporated Bismuth Films.

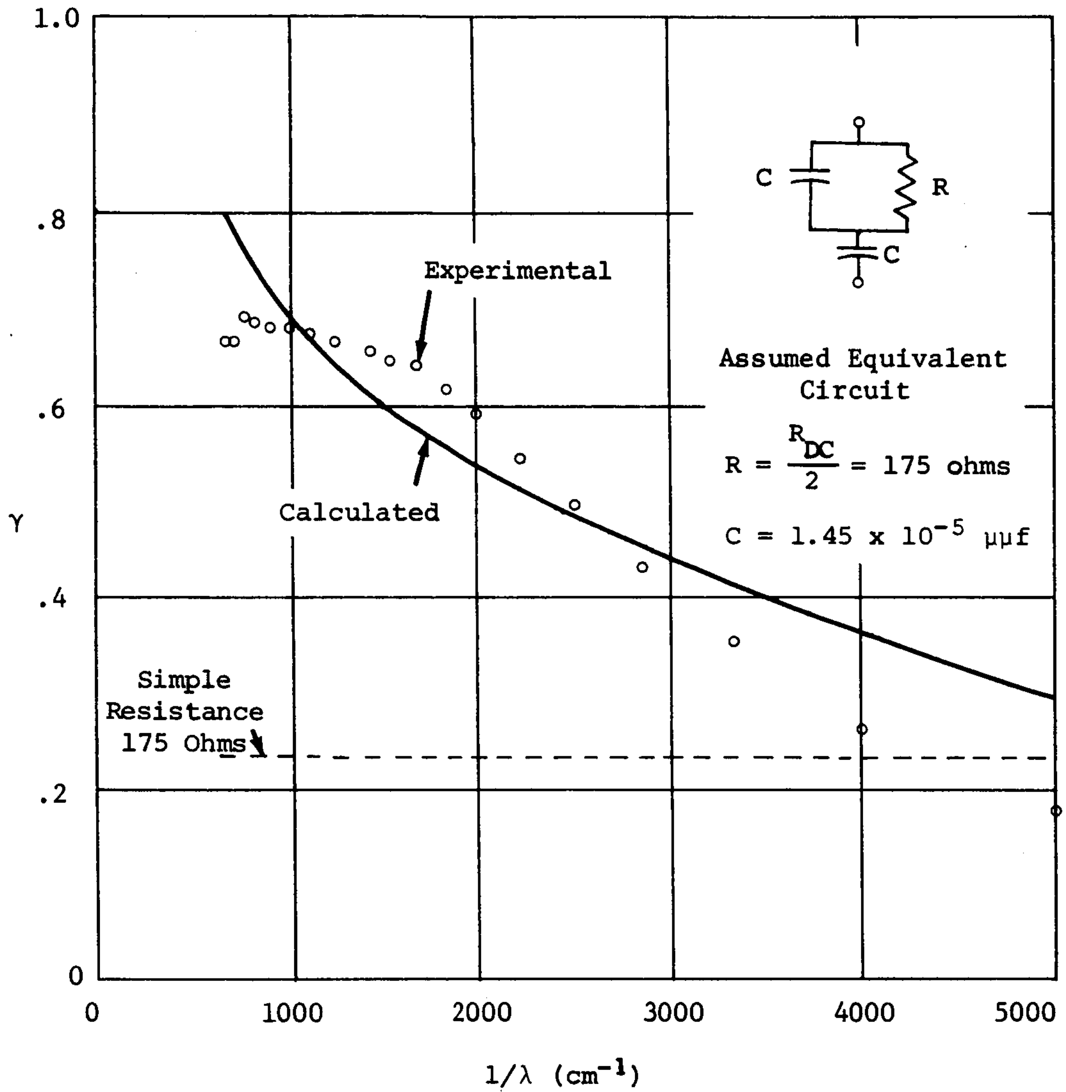


Fig. 23. Calculated and Experimental Transmission Spectra for 350-Ohm Evaporated Bismuth Films.

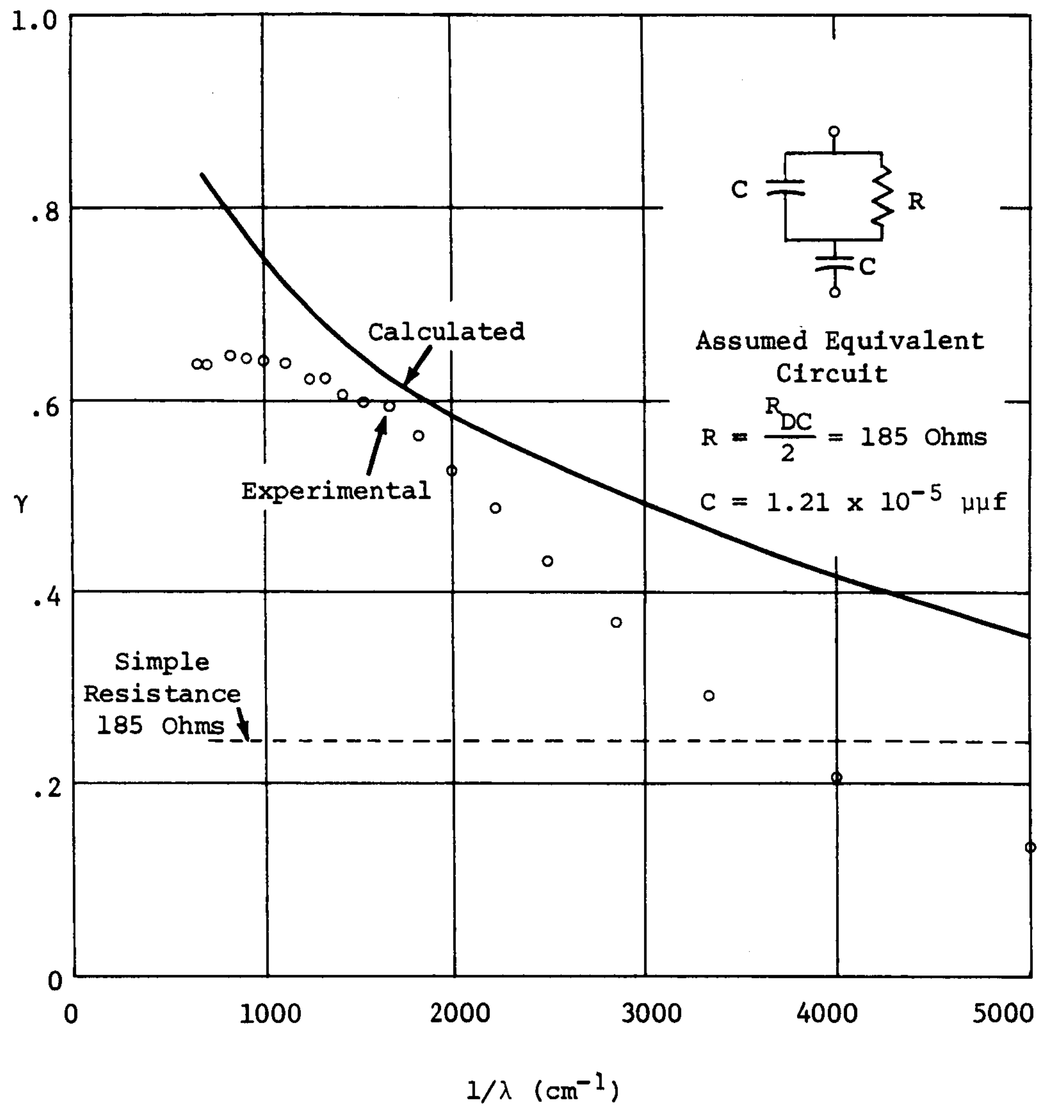


Fig. 24. Calculated and Experimental Transmission Spectra for 370-Ohm Evaporated Bismuth Films.

a final comparison of the results of this research with those from previous work, consider the determination of C for a film having an initial resistance of 100 ohms which was carried out in Fig. 13. The value of 4.2×10^{-5} obtained for the 100-ohm film is a reasonable value when compared with the previously obtained value of 5.3×10^{-5} μμf for a 90-ohm films. It would be expected that the capacitance of this film would be smaller because the film and thus the metal crystallites (whose sides are assumed to form the plates of the inter-grain capacitors[11]) are thinner. This value for C is also compatible with other values for C obtained in this research and listed on Figs. 13, 14, and 15.

When this value for C is used to predict the infrared transmission which might be expected from a film having the series-parallel equivalent circuit, the calculated curve of transmission versus frequency given in Fig. 18 is obtained. It can be seen that this curve agrees best with experimental observations at low frequencies. The agreement is considerably superior to that obtained previously (see Fig. 12) for 90-ohm films at low frequencies. At high frequencies however, the agreement is much poorer, and the series-parallel circuit can only be considered as a reasonable first approximation to an equivalent circuit. This work with the 100-ohm film does, however, reinforce the previous work in validating the heretofore-unknown concept of complex impedance as a useful describing function in the study of conducting thin films.

The work of determining the exact equivalent circuit over a wide range of frequencies is material for other research and was not a goal of the work reported upon herein. In the present research the goal was continuity between this work and previous work, validation of the complex impedance concept for more than a limited case involving 90-ohm films, and an extension of the determination of equivalent circuits to films having a range of values of initial resistances. This work was necessary before irradiation studies could be meaningful. The first part of this goal has been discussed in this section. The next section will be concerned with the extension of the complex impedance concept to other films.

2.3 Determination of Equivalent Circuits For Low-Initial-Resistance Films

Consider now the data presented in Figs. 16 through 24. Each of these figures represents an effort to demonstrate that the series-parallel circuit shown thereon represents the film at infrared frequencies as an equivalent circuit. It should be understood that this implies that the circuit physical dimension is considered to be very much smaller than the wavelengths of the incident radiation being considered. In each case the calculated curve is obtained by assuming that the equivalent circuit shown represents the film, that the value of R is the measured initial resistance divided by two, that C is determined using experimentally obtained infrared transmission data in conjunction with Eq. (13) as discussed previously herein, and that the value of calculated infrared transmission is obtained from Eq. (9). The experimental curve is a plot of measurements of infrared transmission on the film soon after it was deposited by evaporation.

It is seen that the series-parallel circuit is a useful representation for films of all the values of initial resistance except for the highest (370 ohms) over a considerable portion of the spectrum examined, and that the agreement is usually best for lower frequencies. It is clear, however, that certain aspects of the physical characteristics of the films themselves have yet to be accounted for in the equivalent circuit. Even so, these results continue to validate the concept of a complex impedance as a useful describing characteristic for conducting thin films, and indicate that the series-parallel circuit is a good first approximation to an adequate equivalent circuit.

It is desirable to give some further consideration to the validity of the concept of inter-grain capacitance, and particularly to the validity of the values of capacitance determined in Figs. 13, 14, and 15. It was stated previously that the capacitance is assumed to be due to a dielectric of bismuth oxide in the grain boundaries (between the sides of the crystallites). It has been shown[11] that this is a reasonable assumption if one compares the observed physical dimensions of the crystallite boundaries and inter-grain spacings with the dimensions necessary to produce the capacitance values observed. In that work by Howard and Drumheller, films having crystallites whose sides were approximately 1000 A long (determined by electron microscopy) were assumed to have capacitors in their equivalent circuits whose plates were plane, square, and 1000 A on a side. Bismuth oxide was assumed as the dielectric, with a dielectric constant of unity. It was then determined by simple calculation that the capacitance determined for the 90-ohm film, 5.3×10^{-5} μμf, was an expected value provided that one had an inter-grain spacing (or dielectric thickness) of approximately 16 A. Examination of grain boundaries by electron microscopy indicated that 16 A was a good possible value for inter-grain spacing, and thus the capacitance which had been determined seemed acceptable. Subsequently it was determined[5] that 90-ohm films could be expected to have thicknesses of approximately 1470 A. This would indicate that the inter-grain spacing should be 35 A. This is still a reasonable value.

In the same work[5] the values for a wide range of initial film resistances were related to film thickness. That information together with the assumption made previously in calculating the inter-grain spacing required for a given capacitance suggests another way to examine the validity of the concept of inter-grain capacitance. Suppose that one has determined the inter-grain spacing. Then, if the plates of the inter-grain capacitors remain square, the capacitance should be directly proportional to the square of the thickness of the film-- the inter-grain spacing (dielectric thickness) having remained constant,-- and it should be possible to calculate the capacitance corresponding to each value of initial resistance. Experimentally determined values (From Figs. 13, 14, and 15) corresponding to all values of initial resistance should agree. The calculations were carried out and a plot of the theoretical relation between initial resistance and capacitance based on the inter-grain spacing of the 100-ohm film is given in Fig. 25. It is of particular significance that the values of capacitance determined experimentally by the methods described previously (making use of Eq. [13]) when plotted as a function of initial film resistance fall almost on top of the curve of calculated values. The agreement is good, and the concepts of inter-grain capacitance and of complex film impedance are further validated.*

*Neuman[12] has determined that the crystallites of films of bismuth having thicknesses around 800 A are largely columnar in nature, with their average dimensions in the film plane as low as 1/4 of the thickness. With decreasing thickness down to 100 A they change to a "flagstone"-type structure in which the average dimension in the plane of the film varied up to five times the value of their thickness. All of the films described in this report have thicknesses greater than 700 A, varying from 715 A for the 370-ohm film up to 2130 A for the 34-ohm film. The thicknesses were determined from Fig. 2, Reference 5.

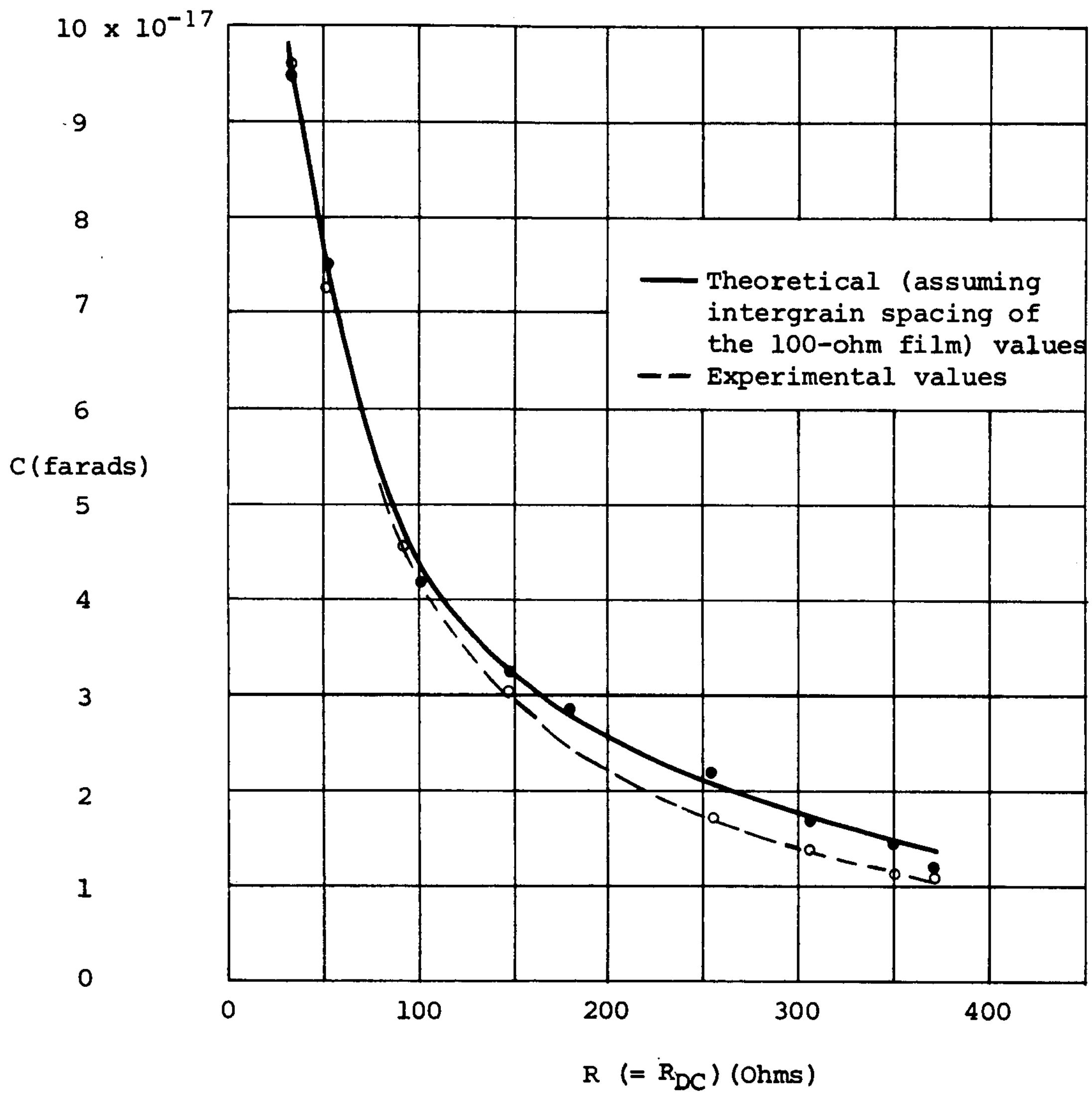


Fig. 25. Theoretical and Experimental Determination of Inter-Grain Capacitance.

3. IMPEDANCE CHARACTERISTICS OF IRRADIATED BISMUTH FILMS

3.1. General Effects of Thin Film Irradiation

The effects of high-energy particles and electromagnetic radiation on metals can be divided into three categories: (1) the excitation of electrons; (2) the permanent or semi-permanent change of the periodic structure of the crystal; and (3) direct and indirect effects of temperature. All of these effects are believed to occur in thin films under electron bombardment, particularly where the electrons have the energies associated with the accelerating potentials of 50, 75, and 100 KV commonly found in the electron microscope. The effect of this bombardment can, for example, cause the generation of excess charge carriers if it is in the first category. Effects of the second category can be expected to include the ejection of atoms from lattice sites, and are not always completely separated from effects of the third category: absorption of energy sufficient to cause melting, re-orientation, and re-crystallization.

It is believed that all three of these effects operate to produce changes in the complex impedance characteristics of thin films, and that if the mechanisms and effects can be established, it will be possible to produce any of a wide range of desirable impedances. It has already been demonstrated[3,4] that changes in the observed structures occur under electron beam irradiation in the electron microscope. They are visible as changes in the appearance (relative darkness) of metal crystallites where these crystallites present a diffraction-contrast pattern rather than an absorption pattern in the electron microscope. Such changes occur only when there is a change in the angle which a crystal plane is presenting to the impinging electron beam. For the films under consideration, the thickness (of the order of magnitude of 1000 A) is such that when the Bragg angle is not satisfied (and the beam deflected) the beam is readily transmitted through the film and presents an absorption pattern on the microscope screen. Now it is expected that these changes (by themselves; other possible changes apart) will affect the conductivity of both the metal and the metal oxides contributing to the impedance characteristics, since conductivity is dependent upon the crystal axis along which the current is flowing.

Determination of change, however, requires a careful control of all the parameters to which the film structure (and therefore the complex impedance) is sensitive both during and after the deposition of the film in order that normal changes may be separable from changes due to irradiation. This research attempted to determine and to evaluate as many of the parameters as possible in the case of thin films of the metal of interest, bismuth. Considerable progress was made and is discussed below.

3.2. Special Problems With Bismuth Films

The first concern in this work was the determination and stabilization of what might be called the film variables. Other variables are those associated with the actual irradiation of the films and will be discussed as irradiation variables later. Film variables include rate of formation, thickness, gas pressure during formation, infrared transmission, initial resistance, and long-term resistance stability.

3.2.1. Deposition Control

Control of the rate of film formation and the final film thickness has been under continuous study and development since the beginning of the project. Specific details concerning the type of source and the rate of film deposition were given in Progress Report 1. The first deposition control unit was built on the project and performed primarily a timekeeping and recording function. It consisted of four interval timers and switching circuitry mounted on a rack panel with two variable transformers and a meter for establishing current levels. The two transformers were used to pre-set the source currents for the evaporation and the pre-heat period preceding the evaporation. The timers recorded the lengths of the pre-heat cycle, the full-heat cycle, the period in which a shutter remained open, and the total elapsed time. The timers were actuated by toggle switches which were thrown sequentially in the course of an evaporation. As an aid to the operator, the unit emitted audible markers at one second intervals.

With this control unit, all control operations were performed manually and were subject to variation from one evaporation to the next and also during a single evaporation. In practice, the current controls were set to pre-determined values and then an entire evaporation took place at that setting. The resistance of one film (out of a group being deposited) was monitored and used to control the length of evaporation. When the resistance of the control film reached the desired value the evaporation was terminated by closing the shutter and turning off the source current.

The source current would drift downward as an evaporation progressed and, when the operator had no other immediate chore, the current was corrected by hand in an attempt to maintain a constant source current. There was no way in which the rate of deposit could be controlled or monitored, and the film thicknesses for each evaporation were not known. A recording of the control-film resistance vs. time was made and qualitative information relative to the constancy of the rate of deposit could be drawn from it; however, it was apparent that both deposition rate and the deposit thickness needed to be known, if not controlled.

A unit manufactured by Sloan Instuments and called the OMNI-I was obtained for evaluation along with a companion silicon-controlled rectifier source power supply and current transformer. This unit is a combination deposit-thickness monitor and rate control, and uses a quartz crystal oscillator in the deposition chamber as a sensing device. The unit which was evaluated had a number of deficiencies, foremost of which was the inclusion of such a large amount of damping in the rate-indicating circuitry that all rate variations were masked entirely. The rate control was a feedback system in which a pre-set rate was compared with the actual rate as indicated by the rate of frequency shift of the crystal oscillator, and the difference was converted to a control voltage for the source power supply. Thus a low rate caused a larger amount of power to be delivered to the source, resulting in the desired increase in deposit rate.

At a later date the laboratory obtained a more versatile version of the unit, the OMNI-II, in which most of the deficiencies of the first unit had been corrected; however, some modifications have been made on it and are considered necessary. These modifications include replacing three single-turn potentiometers on the front panel with ten-turn units and turns-counting dials. This was necessary because the original units could not be set accurately. Two other potentiometers also are inaccurate but they are concentric units and no multiple-turn replacement is available. It has been determined that the timing functions which they control are linear with resistance, however, and the required fixed resistors have been used to replace these potentiometers through a programming plug on the rear of the unit. The necessary equipment has been constructed to open and close the shutter at the proper times during the evaporation sequence. Several distinct evaporations, each for a different film thickness, are being made to calibrate the unit with respect to frequency shift vs. thickness of bismuth. Figure 26 shows the crystal sensing unit in place above the deposition mask. For the calibration, film thicknesses are being determined by use of a multiple-beam interferometer. Following the completion of the calibration curve, the deposit control unit will be used as the film-thickness-measuring instrument as well as the rate control, and its calibration will need to be verified only at intervals. The

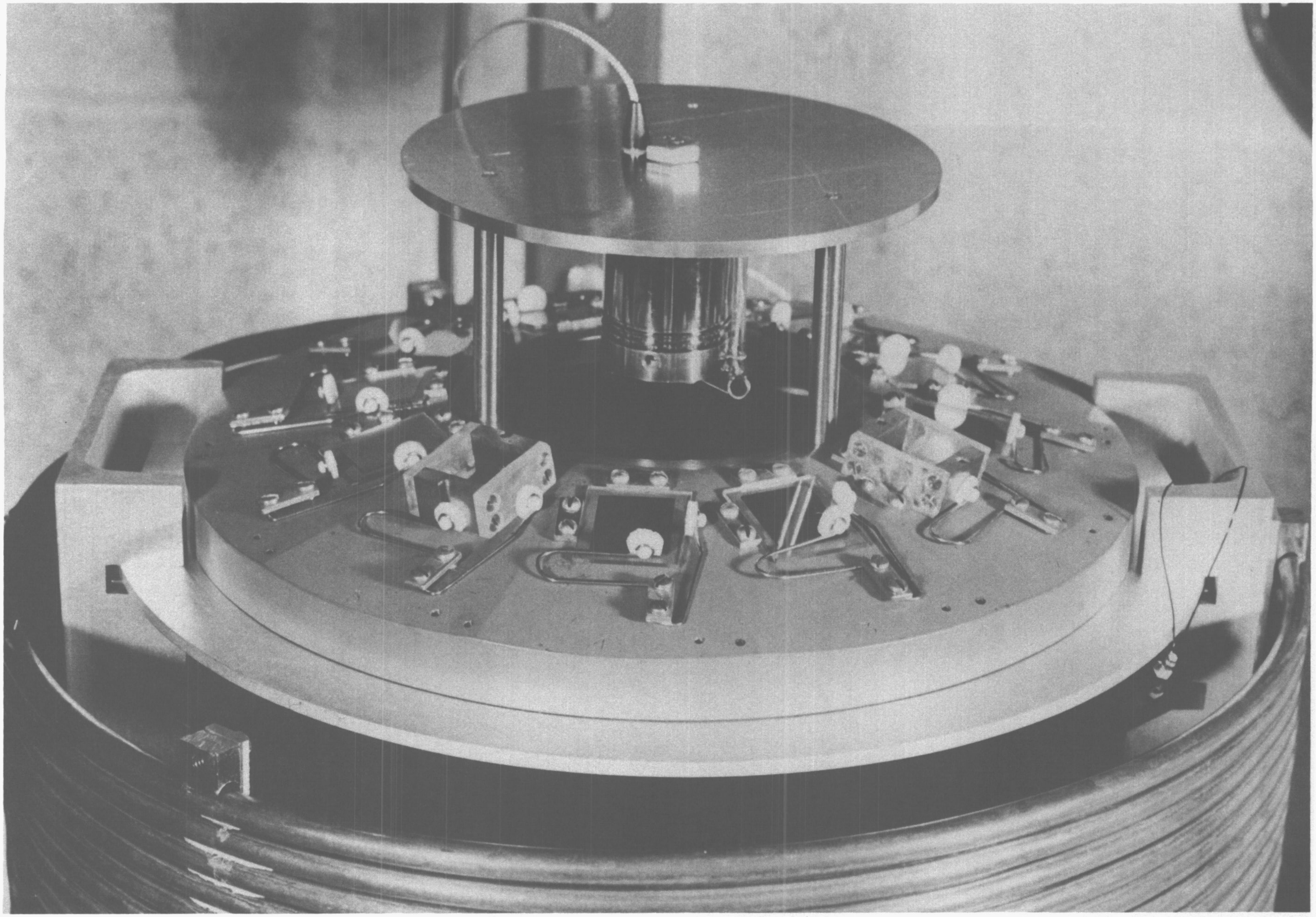


Fig. 26. Mask Detail Showing Thickness Control and Rate Monitor Mounted Above. Two substrate holders are shown in place. Glass substrates (not used in the study) cover the other mask openings.

vacuum system and the associated film deposition control and rate monitoring equipment are shown in Fig. 27.

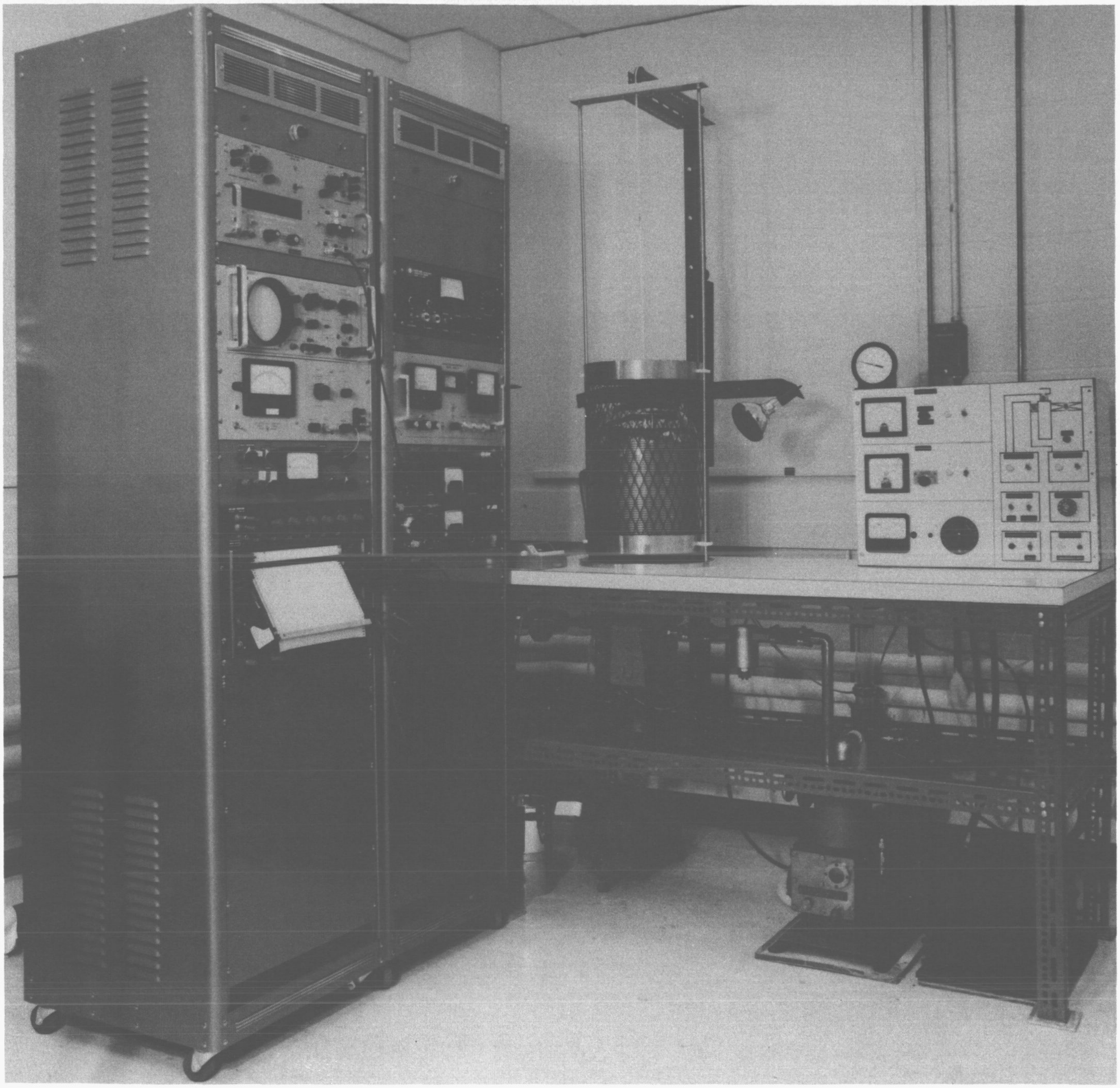


Fig. 27. Vacuum System and Associated Film Deposition Control, Rate Monitoring System, Partial Pressure Analyzer, Low-Power Bridge, and Recording Equipment

3.2.2. Gas Partial Pressure Analysis

A film variable which is of particular importance is the partial pressure of each of the various gases present in the vacuum chamber during film formation. It is believed that these gases are primarily responsible for the formation of inter-grain oxides which constitute the dielectric in the capacitances observed.

In order to determine the amount of each gas present and in order to be able to establish that the amounts of gases present during deposition runs are constant, even though many of those present do not appear to be intimately involved in film formation reactions, the project purchased an AeroVac Model AVA1 Vacuum Analyzer. This instrument uses a Model AST1 Spectrometer Tube which employs two 60-degree sector magnets to cover a total range of approximately 2 to 70 AMU and gives unit resolution to 35 AMU. The unit has been very effective in leak detection, and is producing satisfactorily the necessary information on the partial pressures of gases of interest, particularly oxygen.

3.2.3. Infrared Transmission Characteristics

Establishment of the infrared transmission characteristics of bismuth films is necessary to the determination of the equivalent circuit and the complex impedance for each film. It is important to know how these characteristics vary for films having different values of initial resistance, and also what variation can be expected over a period of time. These film variables have been determined. Figure 29 is a presentation of the transmission characteristics of the bismuth films for which equivalent circuits and complex impedances have been determined in this report. These characteristics were obtained immediately after the formation of the films and correspond to the time at which the initial values of resistances associated with the films

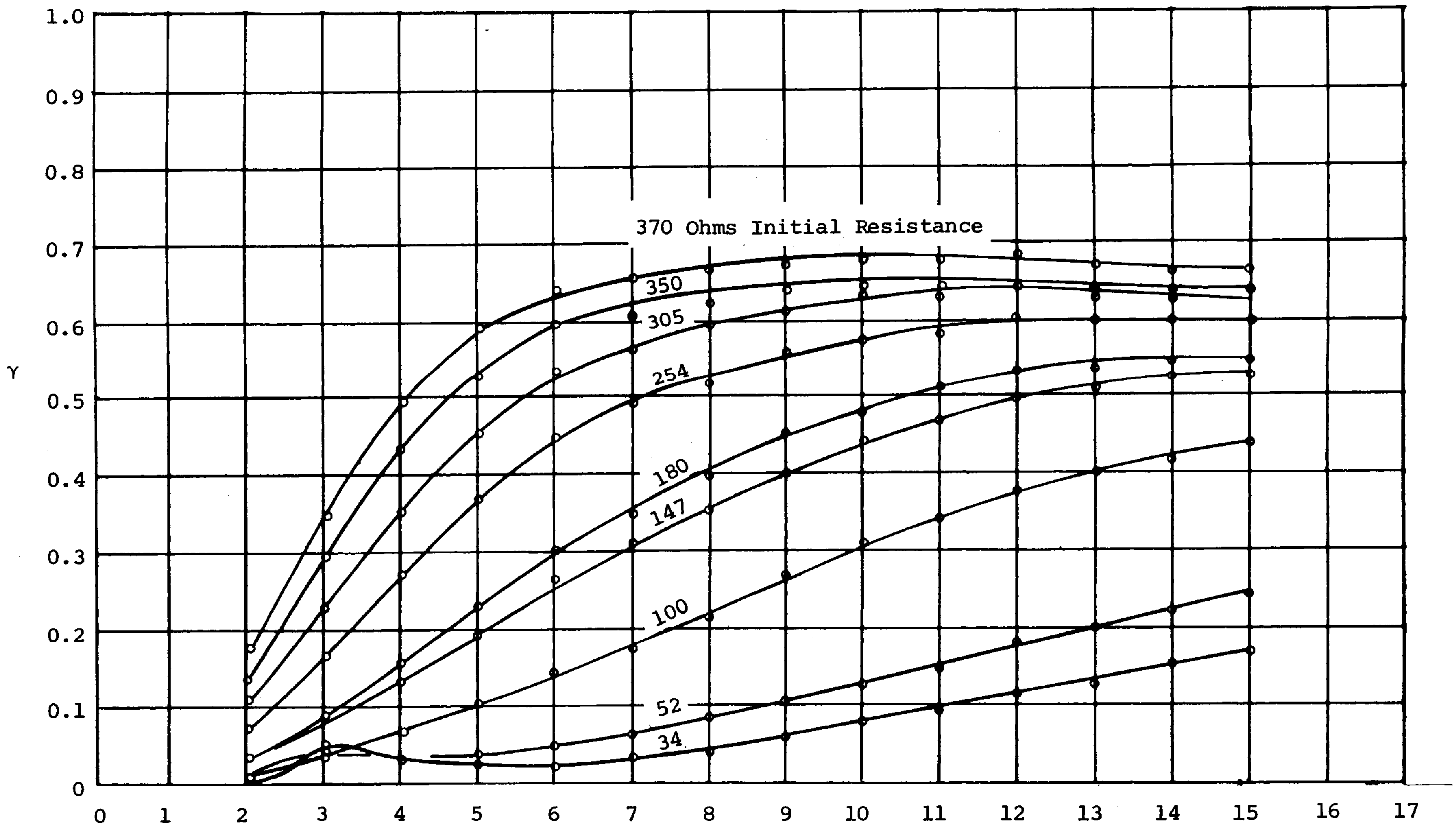


Fig. 28. Infrared Transmission Characteristics of Evaporated Bismuth Films (Substrate: 0.035-μ Cellulose Nitrate).

were measured. The decrease in transmission as one nears the wavelength region of visible light is what would be expected, of course, because all of these films are relatively opaque. Figure 9, already discussed in the determination of transition frequencies is a presentation of the same infrared transmission characteristics as a function of wavenumber.

Figure 29 is a presentation of the transmission characteristics of these same bismuth films approximately six months after formation. If these data are compared with those of Fig. 25, it can be seen that the films having low values of initial resistance changed inappreciably during this period. Infrared transmission of films having high values of initial resistance changed by more than 20% in some cases. It is believed this change is due to oxidation of bismuth. A corresponding presentation of transmission characteristics as a function of frequency is given in Fig. 30. These data will be used in the determination of the change in equivalent circuit structures and complex impedances as a function of time.

3.2.4. Film Resistance Stability

The control of initial resistance, and its consistent reproduction with the same type of structure and in the same length of time, is now assured with the partial-pressure analyzer, the deposition rate control, and the thickness-monitoring equipment. Control of the variation of this initial resistance with time has not been attempted recently. More important information at this time is a knowledge of the way in which the resistance changes under normal ambient conditions. The work of this project has provided that information with the curves of Fig. 31.

Figure 31 is a record of the change of resistance of the films used for the principal work of this project during the past 750 days. These data are in substantial agreement with previous work[2], and indicate a general stability with time for bismuth films below an initial value of 100 ohms.

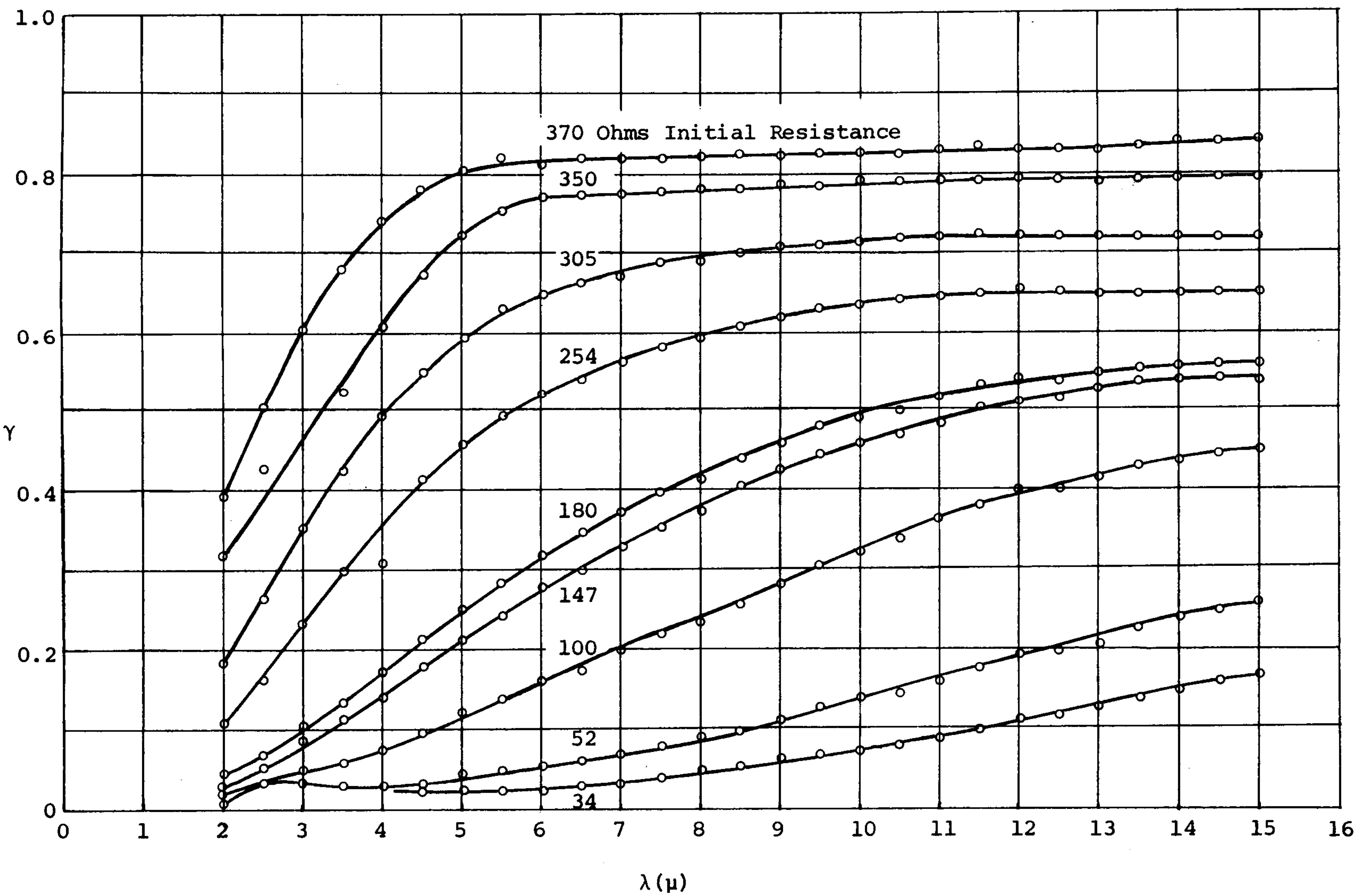


Fig. 29. Infrared Transmission Characteristics of Evaporated Bismuth Films Six Months after Deposition. (Substrate: 0.035-μ Cellulose Nitrate).

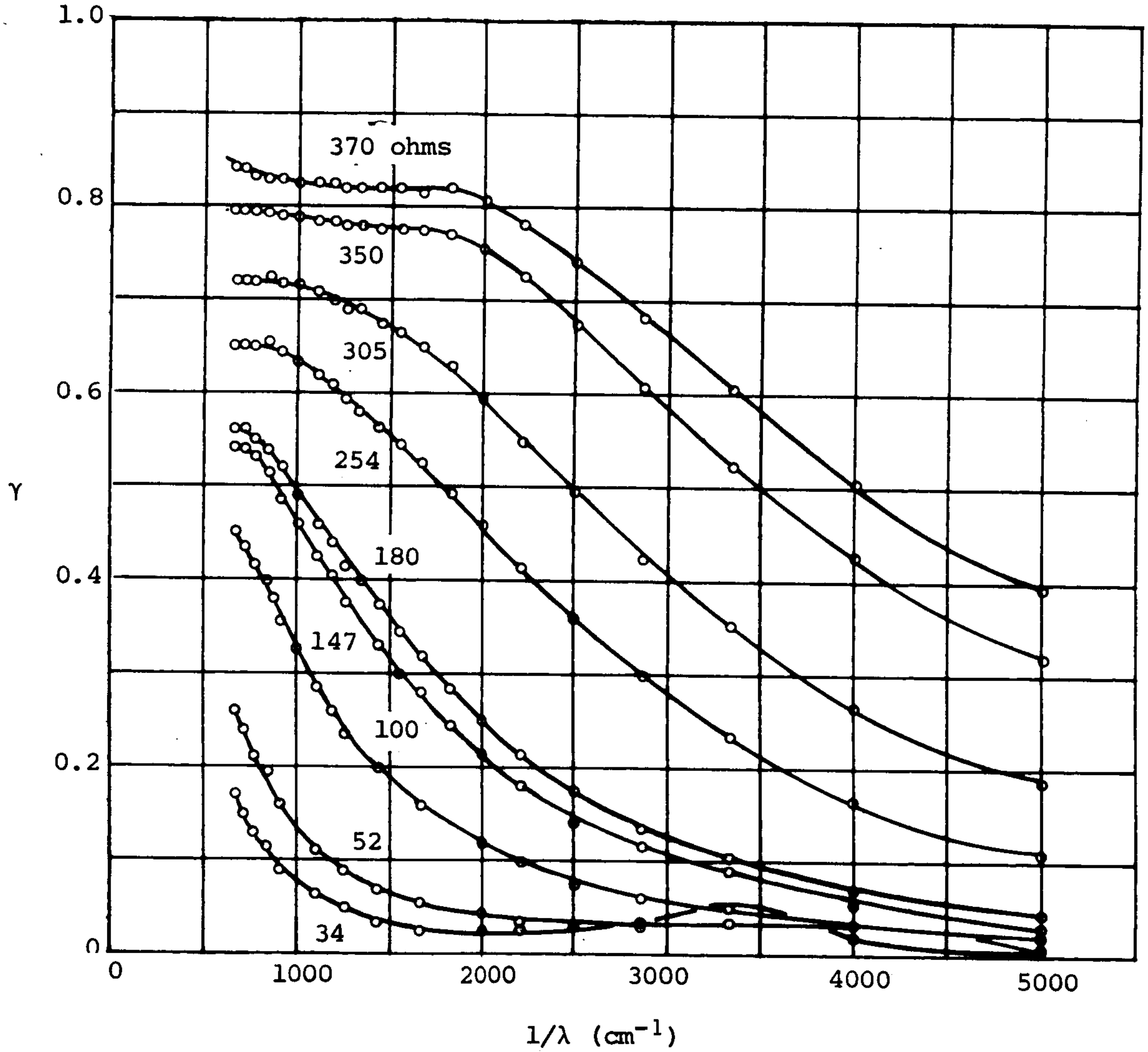


Fig. 30. Transmission Spectra for Evaporated Bismuth Films Six Months After Deposition.

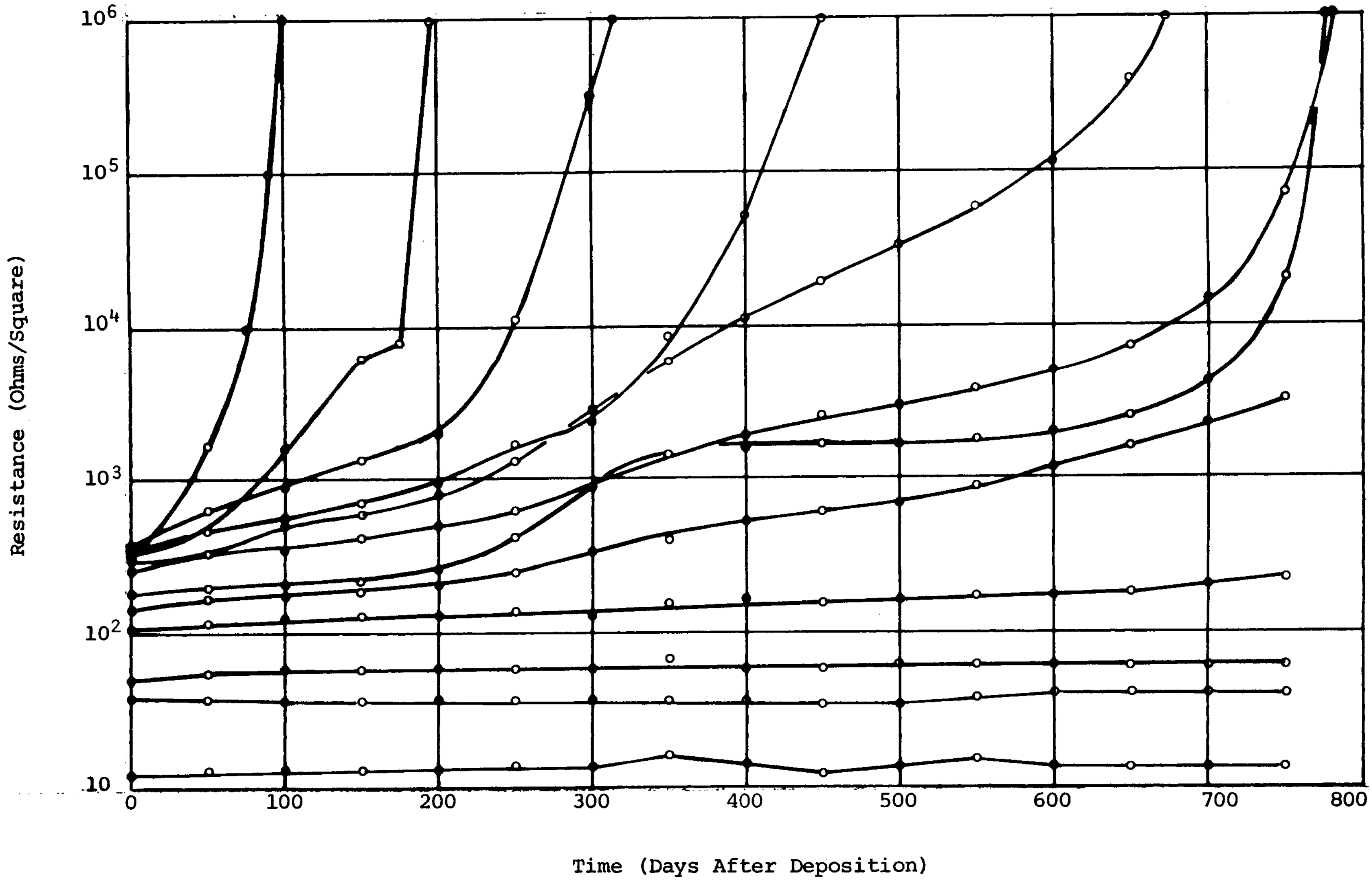


Fig. 31. Drift of Bismuth Film Resistance with Time.

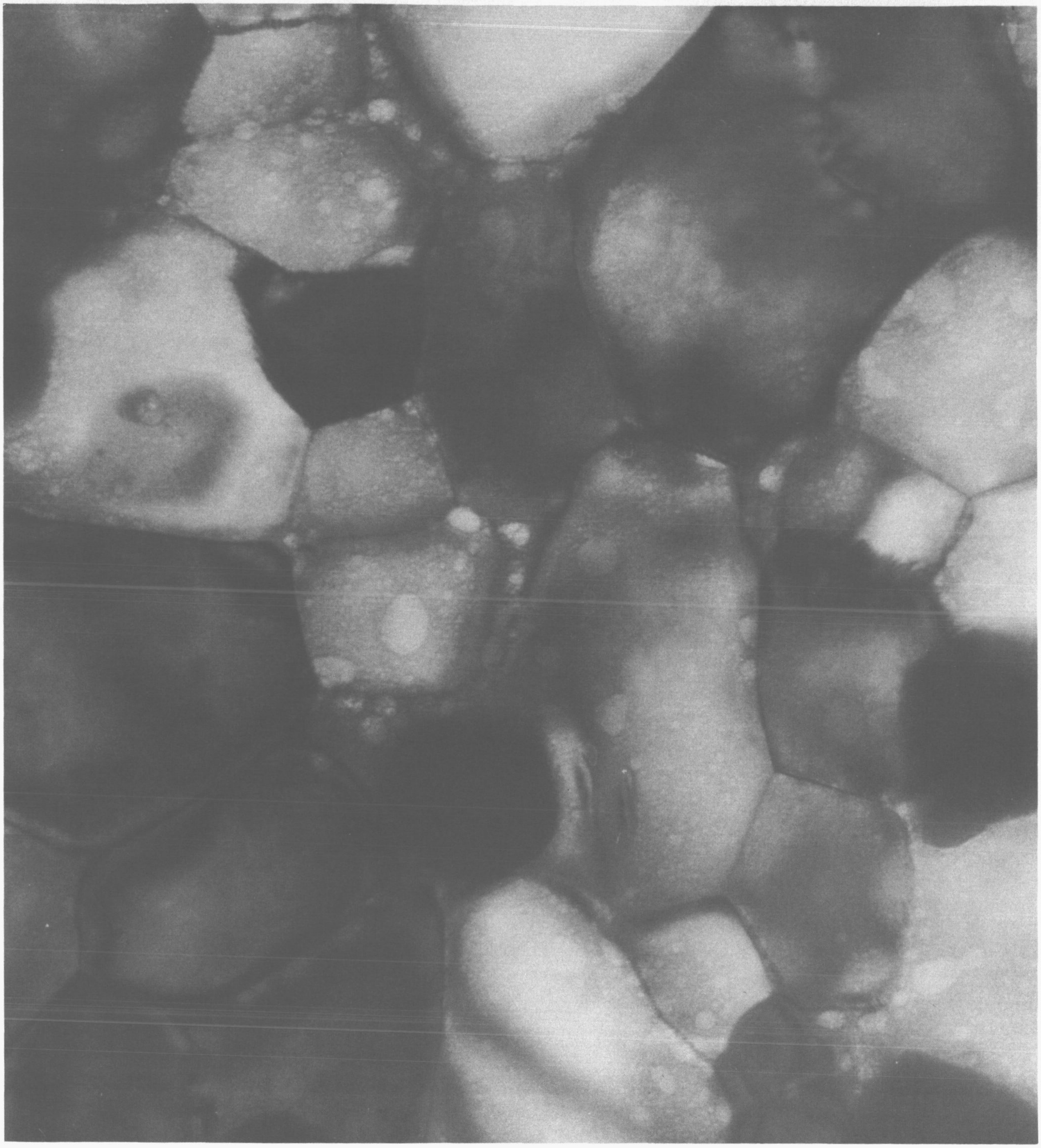
3.2.5. Control of Bismuth Films Under Irradiation Conditions

Progress Report 1 displayed an electron micrograph of a bismuth film of the type this project has considered, and micrographs of this nature have been produced on the University's own microscope since that one was made. Such micrographs are not easily made because exposure of the bismuth film to the beam causes changes in the metal almost immediately. The control of these changes has been the goal of a considerable amount of project effort.

It is clear that specimens from bismuth films of certain thicknesses are easier to control than specimens from others. It is also clear that images are sharper at higher accelerating voltages, yet these voltages produce other effects in the films. It is evident also that LN_2 provides some stability for the crystallites under observation; however, this is not without adverse effects also. Figure 32 is a typical bismuth film electron micrograph which has been obtained with the film cooled to LN_2 temperature. The spots are believed to be caused by bismuth which as been evaporated by the electron beam and then re-deposited on the chilled bismuth surface. Output from other sources of contamination has been systematically reduced so that this seems to be the best postulate at this time. All of these problems have received attention; however, the kind of control which is necessary for moderately long-time (16-30 seconds) study of the film specimens at levels of illumination which enable easy study of inter-grain phenomena, for example, has yet to be achieved.

3.2.6. Miniature Film Holders

In order to obtain electron micrographs of the bismuth films, it is now necessary to sacrifice completely one of the films such as those shown on the holders in Fig. 1. This requires taking a three-millimeter-diameter piece out of the film, thus rendering it unsuitable for further resistance or infrared measurements of the type generally made on it previously. The piece taken



1μ

Fig. 32. Electron Micrograph of Evaporated Bismuth Film Cooled to LN_2 Temperature.

out of the film is mounted on an electron microscope specimen grid for the usual examination in the microscope.

It is not presently possible to make measurements of resistance nor infrared transmission on the mounted specimen; however, it has been one of the goals of this project to develop a specimen support device which would allow making these measurements either in or out of the microscope. This support device with a suitable film substrate on it would be used in the beginning when the bismuth film was being deposited.

A miniature film holder with the following attributes is required for this support.

a. Physical size equivalent to that of an electron microscope grid with a square hole (approximately 1.5 mm on a side) in the center. (A microscope grid is 3.05 mm in diameter and is approximately 0.005 inch thick).

b. The material must be electrically non-conducting to permit film resistance to be measured accurately.

c. The material must not outgas excessively at electron microscope column pressures.

d. The material must be mechanically and dimensionally stable to avoid distortion and breakage of the metal film mounted upon it.

Two types of holders were originally considered most promising. One was made of aluminum with a hard anodized surface finish. The second was made of mylar plastic drafting film with a matt surface. Recently a miniature holder fabricated from glass has been considered as a better possibility.

Each of the first two choices requires a punch of rather critical dimensions and alignment. An attempt was made to utilize an inexpensive universal hard punch manufactured by Whitney-Jenson along with a punch-and-die set made on special order to the dimensions required. This has not been satisfactory for two reasons. First, the punch-and-die set has excessive clearance and does not punch satisfactorily the very thin materials which must be used. A second oversize punch was obtained and ground down by a local machine shop. Although the fit was greatly improved, it still was unsatisfactory for use with the thin materials. The second problem has been the excessive clearance incorporated in the design of the punch itself. This clearance precludes its use in its present configuration even if a perfect punch-and-die set could be obtained for use with it.

Efforts to fabricate a glass miniature-film holder have been somewhat successful. The holder is cut from microscope slide cover glass (which is 0.006 in. thick) by using an Airbrasive unit manufactured by the S. S. White Company. The cutting is accomplished by masking the area of the film holder and directing a stream of abrasive particles at the glass to cut away the unmasked portion.

Samples have been prepared using hand-cut masks of polyvinyl tape. The Airbrasive demonstrator unit which cut the glass was equipped with abrasive powder of the largest size, however, and the edges of the sample were chipped much in the manner of the edge of a hand-made flint arrowhead. The factory engineer gave assurances that the finer abrasive powders would produce a cleaner, better-defined edge, and these other powders will be considered.

A search is now being made to find an ink which will serve as a masking material and which can be silkscreened onto the glass. If this is found, a silk screen will be made by a photographic reduction process which will permit the multiple application of dimensionally accurate masks to the cover glass. These will then be cut out and examined to see if the edges are satisfactory.

SUMMARY AND RECOMMENDATIONS

The results of previous research which postulated the existence of a complex impedance for thin films of bismuth have been verified: results very similar to those previously obtained on two 90-ohm films have been obtained for several 100-ohm films. In addition, it has been possible to validate the previous work with an extension of the theory to include films having resistances ranging from 34 ohms to 350 ohms.

Approximate equivalent electrical circuits have been obtained for bismuth films having initial resistance values ranging from 34 to 350 ohms. These circuits consist of a capacitor in series with a resistor and a capacitor in parallel. The value of the resistor is the initial measured resistance of the film divided by two. The capacitors are equal. Their value is determined graphically making use of transmission line analysis and infrared transmission measurements. The capacitances for these films vary from approximately 1 to 9.6×10^{-5} μμf. The validity of the equivalent circuits is substantiated by comparing the infrared transmission which each equivalent circuit would predict with the actual value of the transmission which the film having that equivalent circuit gave. Substantiation is further validated by a good comparison of predicted values for inter-grain capacitance with the values actually determined graphically.

It has been possible to determine and to control some of the variables which must be kept under surveillance while the effect of irradiation upon the complex impedance of the thin bismuth films is being ascertained. Included is the drift of the resistance of bismuth films. The change of resistance over periods of time up to 750 days has been determined. The change in infrared transmission over certain periods of time has also been determined.

A continuing study of the behavior of bismuth films in the electron microscope has been conducted in order to discover the best way in which to handle both the examination and the irradiation of bismuth specimens. No conclusions can be drawn because of the extreme sensitivity of the bismuth film to the electron beam.

The requirements of miniature film holders capable of successive infrared and resistance measurements and of irradiation in the electron microscope have been determined and are presented.

It is recommended that this research be continued. The radiation studies are desirable; however, it is also important to be able to develop circuits for these films which are equivalent over a wide spectrum of frequencies. Probable immediate benefits from a continuation of these studies includes:

1. The production of circuits of micro-dimension having very high component density.

2. The development of highly sensitive infrared detectors through resonance or absorption effects.

3. The modification of micro-circuits by the electron beam.

4. The coupling to micro-circuits through the electron beam.

5. An improved knowledge of the behavior of thin films in terms of electric circuit theory, enabling their use as fast time-constant sensing devices such as bolometers, for example.

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APPENDIX

The Strengthening of Research Capability

The grant under which the research described in this report was accomplished has enabled a dramatic improvement in the research competence at Southern Methodist University. This is evident in three ways: 1) in the establishment of an electron microscopy laboratory where there was no previous facility of this kind; 2) in the marked improvement of the research capability of the Thin Films Research Laboratory; and 3) in the attraction of new faculty and the resulting establishment of new courses (which will directly support the work of Principal Investigators whose research involves the analysis of microstructure), new research, and enhanced relations with other Universities.

New Electron Microscopy Laboratory

During the first year (1965) of the research grant, NASA awarded an additional grant of $25,000.00 to Southern Methodist University. This money was allocated to the establishment of an electron microscopy laboratory, largely because of the needs of the thin films research project reported upon herein, because of the needs of other NASA projects, and because of the developing needs of other faculty at Southern Methodist University. The University added approximately $55,000.00 to this grant, enabling a completely equipped laboratory to be put into operation in September of 1966. Design and assembly of the laboratory was carried out under the supervision of Professor Lorn L. Howard, Principal Investigator on the thin films project, and with the assistance of the new Laboratory Director, (Mrs.) Venita Allison. The new Electron Microscopy Laboratory extends over approximately 720 square feet of floor space in the Science Information Center. Several air-conditioned rooms are provided for electron microscopy, for specimen preparation, and for photographic work. The Laboratory layout is shown in Fig. 33.

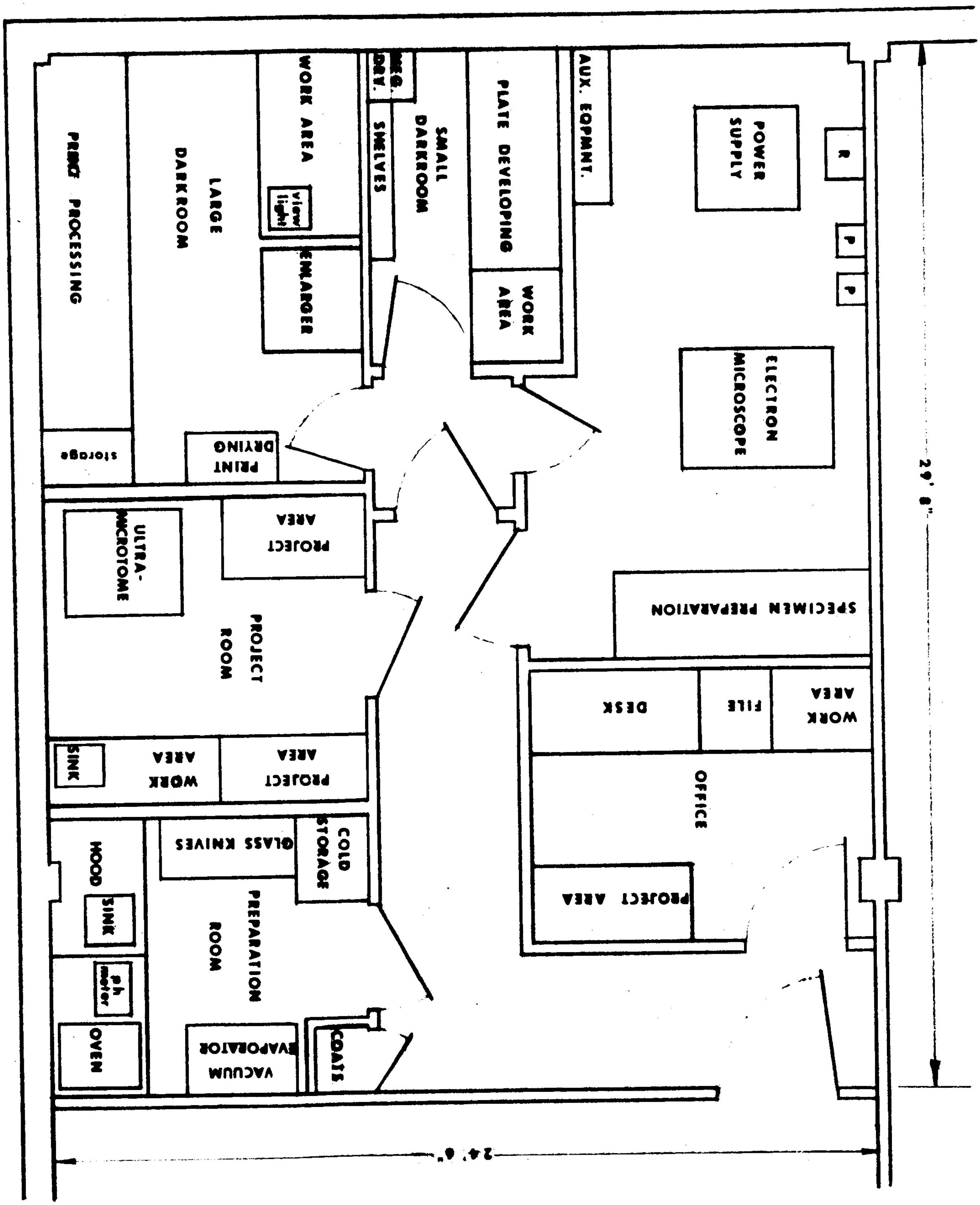

Fig. 33. Electron Microscopy Laboratory

The electron microscope is an Hitachi model HU-11B2 having a magnification of approximately 300,000 times and a resolving power of 6.9 angstrom units. Included with the microscope are accessories which enable electron diffraction, cooling, heating, and cine studies under conditions both of high resolution and high contrast. Available in the laboratory are facilities for shadow casting, ultra-microtomy, knife-making, light microscopy, and refrigeration. The two darkrooms provide facilities for the immediate user of the electron microscope while at the same time allowing printing and other photo-processing activities to proceed in the other darkroom.

The establishment of the Laboratory attracted support from Varian Associates of Palo Alto, California. After the facility was in operation, Varian Associates donated a $15,000.00 MIKROS 20 electron microscope to be used for training and for routine microscopy. This instrument is now located in the Laboratory; however, it is planned to locate it in a separate training facility adjacent to the present Laboratory during the coming year. The proposed plan is shown in Fig. 34.

Thin Films Research Laboratory

The research capability of this laboratory has been improved considerably as a result of the NASA grant. The physical facilities have been expanded; and the amount of scientific equipment available has been increased, both from NASA funds and (because the project was in operation) from other sources. This has enabled the Laboratory to plan more extensive research, and to make research proposals which otherwise would have been impossible. It has also enabled the Laboratory to assist some of the local electronics industry with current problems and with planning for future research and development, both of products and of personnel.

When the grant began the Laboratory occupied approximately 225 square feet of floor space. It has been expanded to include 527 square feet of floor space

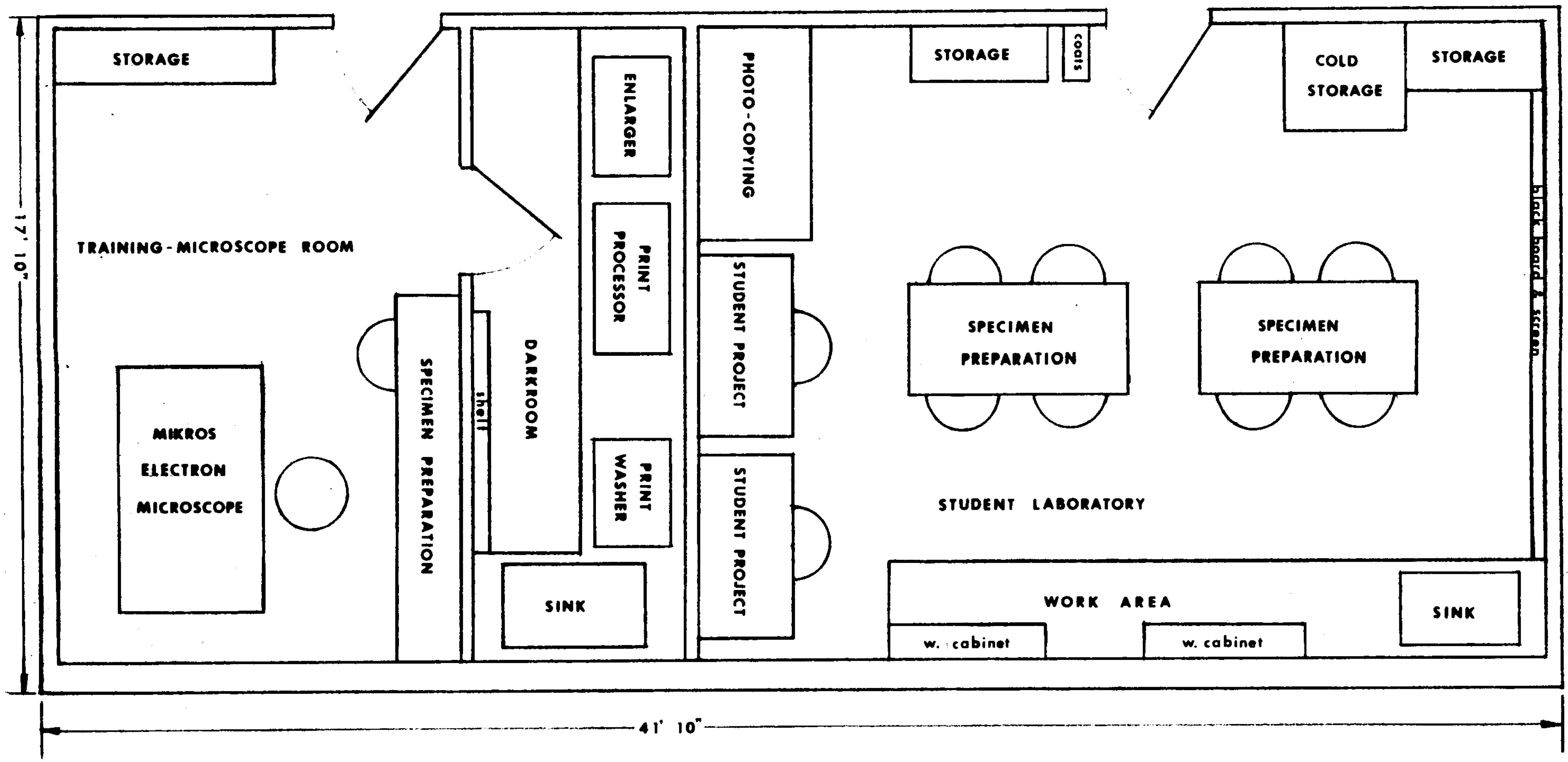

Fig. 34. Proposed Layout of the New Electron Microscopy Training Facility.

in a new air-conditioned building where lighting, power, and other service facilities are considerably improved. The new laboratory was designed by the Principal Investigator for thin films research, and was built by the University.

The principal items of equipment which have enhanced the laboratory capability including a stereomicroscope for the handling of miniature films and electron microscope specimens, and for facilitating the completion of numerous operations involving extremely small tools or components. Also the Laboratory obtained an automatic film deposition rate monitor and thickness control which makes precision control of film formation possible. Further, a mass-spectrometer-type partial-pressure analyzer has been installed, and aids considerably in vacuum system housekeeping activities in addition to its primary function as an indicator of conditions under which thin films are formed "in vacuuo." Also, special accessories (for a Beckman infrared spectrophotometer) to enable the measurement of infrared transmission and reflection on micro-samples have been obtained. These will be important in obtaining infrared characteristics on the miniature films which are under development for irradiation and other studies in the electron microscope. Finally, the addition of the electron microscope discussed in preceding paragraphs has been the greatest benefit to the Laboratory.

Collins Radio Company, a local electronics firm which is developing a thin-film micro-circuit capability engaged the Principal Investigator and (through him) the services of the Thin Films and Electron Microscopy Laboratories during the summer of 1967 in connection with thin-film-circuit problems. The results of this work will be published during 1968. Collins Radio Company indicates that it is planning a continuing use of the Thin Films Laboratory research facilities both for study of some of its basic problems with film circuitry and for the doctoral training of certain selected employees as the result of a proposal from the Principal Investigator. During the period of the research grant this company also donated a used vacuum system and offered further support through permission to use their laboratory equipment (for example, the Tallysurf surface indicator, microscopes, and gauging devices) and through offers to donate small amounts of materials or supplies upon request. These are direct developments of the strengthening of the Thin Films Laboratory which have come about largely as a result of the NASA grant support.

The new capability of the Laboratory places it in an improved position to undertake additional basic thin films research and to provide support for NASA groups working with thin films problems. It is planned to make contact with these groups, and to seek support from other funding agencies.

New Faculty, New Courses, New Research, and New Relations With Other Local Universities

The fact that there was a new electron microscopy facility at Southern Methodist University has been instrumental in the addition of four new faculty members in the Electronic Sciences Center and two new faculty members in the Biology Department. These faculty additions have initiated a considerable number of new courses, including one involving instruction in electron microscopy. The courses include

ES 3245 *Electronic Materials Science I*

ES 4346 *Electronic Materials Science II*

ES 5316 *Transistor Integrated Circuits*

ES 5317 *Integrated Circuits II*

ES 5318 *Integrated Circuit Engineering Laboratory*

ES 5319 *Electronic Processes I*

ES 5320 *Electronic Processes II*

ES 5322 *Semiconductor Materials Technology*

ES 6390 *Seminar in Statistical Electronics*

ES 6391 *Seminar in Thin Film Phenomena and Devices*

Biol 129 *Preparative Techniques for Electron Microscopy*

Biol 128 *Cytology*

Biol 53d *Developmental Biology*

Biol 10 *Principles of Cell Biology* (A revised course)

Chem 108 *Special Topics* (Solid State Chemistry)

In addition, between the new and the old faculty there have been initiated ten new research projects involving as many new graduate students in wide-ranging problems, many of which utilize the Electron Microscopy Laboratory, and thus giving additional strength in graduate training in the Electronic Sciences Center, and in the Physics, Biology, and Geophysics Departments, where these research projects are underway. These projects include

1. A Study of the Structure of Evaporated Bismuth Films
2. Complex Impedance Characteristics of Irradiated Thin Films
3. Transport Phenomena In Thin Films
4. Far Infrared Absorption in Semiconductors With Deep-Lying Impurities
5. The Effects of the Administration of an Adrenal Inhibitor Upon the Cells of the Adrenal Cortex and the Anterior Pituitary
6. A Preliminary Investigation of Myofilament Formation in Uterine Muscle
7. Calcium Transport in the Hypodermis of the Crayfish
8. Studies of the Fine Structure of a Solid Carbonate
9. Surface Damage to Silicon Devices Applied in Space Vehicles
10. Electron Microscopy of the Glazed-Aluminum-Oxide Substrate Surface

Significant also are programs being initiated with other local universities. Southwestern Medical School (of the University of Texas in Dallas) graduate students in the Department of Anatomy are now encouraged to enroll in the course Biol 129 listed above covering preparative techniques in electron microscopy of biological materials. Three semester hours credit are given for this course, which includes lectures, seminars, and practical laboratory experiences. In return, students at Southern Methodist University are invited to participate in certain graduate courses at the Medical School such as the Seminar in Electron Microscopy, Special Problems in Anatomy, and Research Problems in Anatomy.

Baylor University Medical Center invites Southern Methodist University students and faculty participation in Center activities which include the application of the electron microscope. In return the staff at Baylor are invited to enroll in SMU courses in Biology (including Biology 129) which can provide certain necessary academic background.

A Texas Christian University faculty member has made arrangements to use the electron microscope and to initiate problems of mutual interest to him and to the Laboratory Director. In return he would supply funds, make certain equipment available to local students, and assist in seminars and other activities associated with the Electron Microscopy Laboratory.

The electron microscope is available to all faculty members. The Laboratory itself is not now located in any departmental administrative structure. Instead, its operations are supervised by a policy-setting committee of users among the faculty.